ExoMars

Science Management Plan

Version 6.0
31 January 2014

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1 INTRODUCTION AND SCOPE

Establishing whether life ever existed, or is still active on Mars today, is one of the outstanding scientific questions of our time. The ExoMars Programme seeks to timely address this and other important scientific goals, and to demonstrate key flight and *in situ* enabling technologies underpinning European and Russian ambitions for future exploration missions. The ExoMars Programme is a cooperative undertaking between the European Space Agency (ESA) and the Russian federal space agency, Roscosmos.

Within ESA, ExoMars is an element of the Aurora Exploration Programme, an optional programme executed under the supervision of the Programme Board for Human Spaceflight, Microgravity and Exploration (PB-HME). However, the ESA Science Programme also participates to ExoMars. The objective of the Aurora Programme is to explore Solar System objects having a high potential for the emergence of life. Aurora aims to develop technologies and address scientific questions in a step-wise fashion, seeking to advance the level of technical and scientific readiness with each successive mission.

Within Roscosmos, ExoMars is part of the Russian federal space programme and is supported by the Russian Academy of Sciences.

To prepare for future exploration missions and to support the Programme's scientific objectives, ExoMars will achieve the following technology objectives:

- **Entry, Descent, and Landing (EDL) of a payload on the surface of Mars;**
- **Surface mobility with a Rover;**
- **Access to the subsurface to acquire samples;**
- **Sample acquisition, preparation, distribution, and analysis.**

In addition to these technology objectives already agreed in the Aurora Declaration, the following new technology objectives result from the cooperation with Roscosmos:

- **Qualification of Russian ground-based means for deep-space communications in cooperation with ESA's ESTRACK;**
- **Adaptation of Russian on-board computer for deep space missions and ExoMars landed operations;**
- **Development and qualification of throttleable braking engines for prospective planetary landing missions.**

The scientific objectives of ExoMars are:

- **To search for signs of past and present life on Mars;**
- **To investigate the water/geochemical environment as a function of depth in the shallow subsurface;**
- **To study martian atmospheric trace gases and their sources.**

In addition to these science objectives already agreed in the Aurora Declaration, the following new scientific objective results from the cooperation with Roscosmos:

- **To characterise the surface environment.**

The ExoMars Programme consists of two missions, in 2016 and 2018. ESA and Roscosmos have agreed[1] a well-balanced sharing of responsibilities for the various mission elements.

The 2016 mission will be launched on a Roscosmos-provided Proton rocket. It includes the Trace Gas Orbiter (TGO) and an Entry, descent and landing Demonstrator Module (EDM), both contributed by ESA. The TGO will carry European and Russian scientific instruments for remote observations, while the EDM will have a European payload for *in situ* measurements during descent and on the martian surface.

The 2018 mission will land a Rover, provided by ESA, making use of a Descent Module (DM) contributed by Roscosmos. The DM will travel to Mars on an ESA-provided Carrier Module (CM). Roscosmos will launch the spacecraft composite on a Proton rocket. The Rover will be equipped with a European and Russian suite of instruments, and with Russian Radioisotope Heating Units (RHUs). The Rover will also include a 2-m drill for subsurface sampling and a Sample Preparation and Distribution System (SPDS), supporting the suite of geology and life seeking experiments in the Rover's Analytical Laboratory Drawer (ALD). The Russian Surface Platform (SP) will contain a further suite of instruments, mainly concentrating on environmental and geophysical investigations.

NASA will also deliver important elements to ExoMars: The Electra Ultra-High Frequency (UHF) radio package on TGO for Mars surface proximity link communications with landed assets (such as the Rover and Surface Platform); engineering support to EDM; and a major part of MOMA, the organic molecule characterisation instrument on the Rover.

This Science Management Plan (SMP) specifies in detail the scientific management of the ExoMars Programme, focusing on the way the payloads are selected and implemented for the various mission elements as a joint effort of the scientific community, the funding organisations, ESA and Roscosmos. The modes of participation of the scientific community in the programme are addressed, as well as the responsibility of ESA/Roscosmos and their teams vis-à-vis the missions' implementation and exploitation. Finally, the data rights and responsibilities of the involved scientists are explained, as is the data analysis policy.

The ExoMars Science Management Plan is applicable to all parties wishing to participate in the ExoMars Programme. Although the SMP *per se* is not legally binding on Roscosmos, Roscosmos is nonetheless bound by its provisions to the extent agreed upon under the ESA-Roscosmos Agreement concerning Cooperation on the Robotic Exploration of Mars and other Bodies in the Solar System ("the Agreement). In this respect one can take the examples of article 12.5 of the Agreement regarding the scientific data policy, and article 9.6 regarding the role of the ExoMars Science Working Teams (SWTs).

Whenever mission or programmatic developments justify a revision, the ExoMars Science Management Plan will be updated and resubmitted to the Advisory Bodies for endorsement and to the Programme Board (PB-HME) and Science Programme Committee (SPC) for approval.

[1] Agreement between the European Space Agency and the Federal Space Agency (the Russian Federation) concerning cooperation on robotic exploration of Mars and other bodies in the Solar System, signed 14 March 2013 [Ref. ESA/C(2013)19].

2 EXOMARS SCIENCE OBJECTIVES

Establishing whether life ever existed, or is still active on Mars today, is one of the outstanding scientific questions of our time. Both ExoMars missions will address this important goal. They will also pursue other complementary science objectives to improve our understanding of the martian environment.

The ExoMars programme's scientific objectives are:

1. To search for signs of past and present life on Mars;
2. To investigate the water/geochemical environment as a function of depth in the shallow subsurface;
3. To study martian atmospheric trace gases and their sources;
4. To characterise the surface environment.

Starting with the first, and proceeding in order, this Section describes the way the scientific objectives are targeted by the various mission elements (see Table 1).

The ExoMars Rover will address the first two objectives, the search for life and the characterisation of the subsurface water/geochemical environment as a function of depth. In the course of its mission, the Rover will perform numerous surface investigations on outcrops and soils, also contributing to the fourth objective.

The Trace Gas Orbiter will concentrate mainly on the third objective, but will achieve valuable science progress on objectives 1, 2 and 4.

The ExoMars Surface Platform will conduct environmental and geophysical measurements in support of the fourth objective. These results will also provide important context information for objective 1, benefiting also the Rover mission.

Finally, the EDM surface payload will contribute to furthering the fourth scientific objective.

Mission Element	Coverage of Scientific Objectives
Trace Gas Orbiter (TGO)	Mainly 3, with valuable contributions to 1, 2, and 4.
EDM	Concentrates on objective 4.
Rover	Strongly focused on 1 and 2, with important *in situ* contributions to 4.
Surface Platform (SP)	Deals mainly with 4, providing context information for 1.

Table 1: Coverage of programme's scientific objectives by each ExoMars mission element.

Besides the investigations that will be possible to conduct with each element, the ExoMars Programme includes an excellent potential for cross-platform scientific studies not often found on other missions. For example, coordinated measurements between the Rover and TGO may be conducted to provide insights into the past and present habitability of Mars. Likewise, the Surface Platform and Rover will be able to image each other, and may carry out joint scientific measurements during the first part of their surface mission, while they are close together.

For a more complete description of the various mission elements' scientific objectives, please refer to Annex 1. Annex 2 presents more details on the instruments and their team organisation. Additional ExoMars background information, including a brief historical summary of the work leading up to the programme's present status, can be found in Annex 3.

2.1 ExoMars 2016 Mission Summary

The 2016 mission will pursue the following science objectives: It will study martian atmospheric trace gases and their sources, contributing to the search for signs of possible present life on Mars. The latter will be pursued through a careful analysis of the association among minor atmospheric constituents and isotope ratios. The TGO will also investigate the planet's surface and subsurface.

The EDM will land on Mars and conduct *in situ* environmental measurements.

Table 2 provides a summary description of the 2016 mission's main milestones.

Spacecraft:	Trace Gas Orbiter (TGO) plus Entry, descent, and landing Demonstrator Module (EDM)
Launch:	Jan 2016, from Baikonur on a Proton M (backup in May 2018).
Arrival:	Oct 2016 (backup in Jan 2019).
TGO Orbit:	Circular, 400-km altitude, 74º-inclination, with an approximately 30-sol repeat pattern. Achieved after aerobraking completion (by Nov 2017).
EDM Landing:	Direct entry, from hyperbolic trajectory, during the dust storm season. Landing site: Meridiani Planum (1.82º S, 6.15º W). Maximum altitude: –1 km, relative to the MOLA zero level. Uncertainty ellipse: 100 km x 15 km.
Science:	TGO: Trace gas science, imaging, and top subsurface hydration. EDM: Descent science and environmental station. Wet Mass: 4332 kg, including 600-kg EDM. TGO lifetime: Until end 2022 (nominal science time is 1 martian year). EDM lifetime: 2 sols.
Ground Segment:	Mission operations centre: ESOC. Science operations centre: ESAC. Mission science archives: ESAC and IKI.

Table 2: ExoMars 2016 mission information.

2.2 ExoMars 2018 Mission Summary

The 2018 mission will address mainly the programme's first two science objectives. The ExoMars Rover will carry a comprehensive suite of instruments dedicated to exobiology and geology research named after Louis Pasteur. The Rover will be able to travel several kilometres searching for traces of past and present signs of life. It will do this by collecting and analysing samples from within outcrops, and from the subsurface—down to 2-m depth. The very powerful combination of mobility with the ability to access locations where organic molecules can be well preserved is unique to this mission.

After the Rover will have egressed, the ExoMars Surface Platform (SP) will begin its science mission to study the surface and subsurface environment at the landing location.

Table 3 presents the 2018 mission's principal features.

Spacecraft:	Carrier Module (CM) plus 2000-kg Descent Module (DM), including Rover and Surface Platform (SP). Data relay function to be provided by TGO.
Launch:	May 2018, from Baikonur on a Proton M (backup in Aug 2020).
Arrival:	Jan 2019 (backup in Apr 2021).
Landing:	Direct entry, from hyperbolic trajectory, after the dust storm season. Landing site: To be defined. Must be safe and appropriate for "search for life" science. Latitudes between 5º S and 25º N, all longitudes. Maximum altitude: –2 km, relative to MOLA zero level. Uncertainty ellipse: ~100 km x 15 km.
Science:	Rover with Pasteur payload: Mass 310 kg, including drill/SPDS and instruments. Lifetime 218 sols. Surface Platform: SP Instruments to be defined. Lifetime 1 martian year
Ground Segment:	Mission operations centre: ESOC. Rover Operations Control Centre: ALTEC. Surface Platform operations: IKI. Mission science archives: ESAC and IKI.

Table 3: ExoMars 2018 mission information.

3 PROGRAMME PARTICIPATION

3.1 Modes of Participation

The ExoMars Programme's missions are open to investigators from all countries. Principal Investigators have to be based in an ESA member state or in Russia.

The possible modes of participation in ExoMars missions are:

1. Principal Investigator (PI): The scientist that coordinates and represents a team providing an instrument. He/she is the main point of contact for ESA/Roscosmos
2. Co-Principal Investigator (Co-PI): A Co-PI appointment recognises a major instrument development carried out in a country/institution different from that of the PI.
3. Co-Investigator (Co-I): A member of an instrument team providing an instrument.
4. Interdisciplinary Scientist (IDS): An expert in specific scientific subjects supporting the multidisciplinary nature of the ExoMars Programme. An IDS makes synergistic use of the data delivered by several instruments, or by various mission elements, to address scientific or technical issues considered important for the ExoMars Programme.
5. Guest Investigator (GI): A scientist participating in the data collection and analysis of one or more instruments, and/or performing laboratory studies, theoretical, or numerical investigations essential for mission success.

Previous Rover Pasteur payload Team Coordinators (TC), Deputy Team Coordinators (DTC), and Team Members will be considered PIs, Co-PIs, and Co-Is respectively.

3.1.1 Principal Investigator

Within the remits of the Rover Instrument Multilateral Agreement (IMA) and the ExoMars 2016 Instrument Agreement, a Principal Investigator, or, where applicable, a Lead Funding Agency representative, will have the following responsibilities:

1. Management:
    a. Represent the instrument team and be the ultimate responsible person, with respect to ESA/Roscosmos for all matters concerning the instrument's science definition, development, performance, operations, data reduction, and product archiving.
    b. Organise the planned commitments and contributions from the instrument consortium.
    c. Organise the efforts, assign tasks, and guide the instrument consortium.
    d. Establish an effective management scheme to be used for all aspects of the instrument project, technical and scientific.
    e. Ensure that the instrument project's plans and schedules are properly established and respected, such that the ExoMars Project's requirements can be timely met.
    f. Timely report to the ExoMars Project the status of all instrument project activities.
    g. Support ESA management requirements (e.g. investigations, progress reviews, change procedures, product assurance, planetary protection, etc.), outlined in the instrument E-ICD.
    h. Where applicable, be responsible for ensuring the instrument team's timely compliance with all International Traffic in Arms Regulation (ITAR) dispositions. ESA will provide the necessary support to the PI. Any surveillance requirements arising from ITAR shall be reported to ESA immediately. Costs associated with the fulfilment of such requirements shall be borne by the PI.

2. Science:

   a. Assume a full and active role in the instrument's science definition and development.

   b. Maintain, at all times, a constructive and positive spirit within the instrument science team, and vis-à-vis other instrument teams.

   c. Seek a fruitful cooperation with all instrument teams, openly sharing information, with the goal to maximise the programme's science return.

   d. Monitor the compliance of the instrument's design with the scientific requirements contained in the "Scientific Payload Requirements Document."

   e. When so requested by ESA, attend meetings of the Science Working Team, Advisory Bodies, and Industry—as appropriate—to support mission definition activities.

   f. Ensure the scientific relevance and robustness of the instrument's results. This includes, *inter alia,* adequate verification and calibration of all instrument parts and elements, both on the ground and later in space; timely and thorough testing of the instrument's science using representative natural samples in mission-relevant conditions; etc.

   g. Provide regularly to the ExoMars Project progress reports on instrument development status, scientific verification, laboratory and field test results, etc.

   h. Actively and regularly inform the scientific community at large—in meetings and publications—of progress in the instrument's definition, its science, and its intended use in the ExoMars missions.

   i. Support the utilisation of the instrument's science by the scientific community:

      - Deliver a complete instrument "Technical and Science User Manual" in Word format. ESA and Roscosmos will make this document available for download once the data are made public.

      - Provide ESA and Roscosmos with all calibration information necessary to allow others to effectively use the instrument's data;

      - Provide simulated data streams to test the correct functioning of the data distribution and analysis service;

      - Timely provide all mission science data (raw data, calibrated data, and higher-level data), including all necessary calibration products and software, to the ExoMars archive in a format that will be agreed by ESA, Roscosmos, and the ExoMars missions' science community.

   j. In coordination with all other Rover, TGO, EDM, and SP scientists, exploit the ExoMars missions' scientific results in an effective manner; and ensure their publication as soon as possible—in accordance with the ExoMars publication rules.

3. Hardware:

   a. Coordinate the definition of the instrument's functional requirements, and of those of its auxiliary equipment (e.g. MGSE, EGSE, etc.).

   b. Ensure the overall development, construction, testing and delivery of the instrument, in accordance with the technical and programmatic requirements defined by the ExoMars Project.

   c. Manage and update the evolution of all instrument interfaces, ensuring that they are accurately reflected in the relevant E-ICD.

   d. Ensure that the development, construction, testing, and delivery of the instrument are appropriate to the objectives and lifetime of the mission, and to the environmental and interface constraints under which it must operate.

   e. Deliver adequate instrument verification models (EQM, STM, etc.) to the ExoMars industrial consortium, as required to verify system interfaces. What exactly is required is defined in the applicable E-IRD.

f. Deliver an instrument Flight Model (FM) and Flight Spares, in accordance with the technical requirements defined in the applicable E-IRD.

g. Support the system-level integration and test activities related to, or involving, the instrument.

h. Provide all equipment necessary to process and interpret the instrument data, as agreed with ESA and Roscosmos, and defined in the applicable E-IRD.

i. Ensure that all instrument hardware is compliant with ExoMars Project requirements, through participation in technical working groups and control boards (i.e. for organic cleanliness), as requested, and that the hardware allows system level performance compatibility to be maintained.

j. Ensure that the mission's system level performance (technical and scientific) can be maintained, and is in no way impeded or compromised by any instrument-related factors, either due to instrument team's actions or omissions.

k. Timely deliver to the ExoMars Project all required instrument project documentation, as defined in the applicable E-IRD.

4. Software:

a. Ensure the timely development, testing, and documenting of all software necessary, in accordance with the rules and guidelines stipulated in the E-IRD.

b. Specify and support the development, testing, and documenting of all software required for the verification, operation, and data reduction/analysis of all instrument parts or elements, including those built or provided under ESA responsibility, in accordance with the rules and guidelines stipulated in the E-IRD.

c. Ensure the timely delivery to ESA of any instrument-specific software needed for instrument testing or operation in accordance with ESA-approved guidelines, procedures, and schedules. This includes any software required by the SOC or ROCC, as specified in the applicable Science Operations Requirements (SOR) document.

d. Maintain and update all instrument software and documentation until the end of the mission. This includes all agreed PI-provided software to be delivered to the SOC or ROCC as part of the final archive.

5. Product Assurance:

Provide Product Assurance (PA) functions in compliance with the applicable E-IRD requirements.

6. Planetary Protection:

Provide Planetary Protection (PP) functions in compliance with the applicable E-IRD requirements.

7. Operations:

Provide support for the preparation and implementation of ExoMars operations, up to the end of the mission(s), in compliance with the applicable E-IRD requirements. This will likely imply being physically present (at least during the first few months) at the ROCC to assist with Rover science operations.

a. Participate to the definition of the science operations and data handling service.

b. Support the Science Operations Centre (SOC) and the Rover Operations Control Centre (ROCC).

c. Support the real time verification and analysis of the instrument science results to assist with the ExoMars mission planning activities and surface operations.

8. Financial Aspects and Relation to Lead Funding Agency:

Financial support for the Principal Investigator and his/her immediate collaborators will have to be guaranteed by the instrument's Lead Funding Agency. The Lead Funding Agency will also be considered responsible vis-à-vis ESA for the coordination of all financial matters related to the specific instrument, including, but not limited to, the procurement of instrument contributions in the form of elements, parts, software, or support from institutes in other countries. All team members are required to seek agreement with the instrument's Lead Funding Agency. A Lead Funding Agency representative may participate as observer, as required, to major meetings and reviews. The successful agreement between all Lead Funding Agencies is formalised in the proper agreements, e.g. Instrument Multilateral Agreement (IMA). The signature of the IMA by all Lead Funding Agencies is a prerequisite for the confirmation of the instruments in an ExoMars mission. Thereafter, the Lead Funding Agency becomes ESA's sole point of contact for all financial matters concerning the specific instrument project. The Lead Funding Agency has the overall financial responsibility for the instrument project's success.

In case the Principal Investigator, for any reason and at any time in the project, must withdraw or resign from his role, he/she will send a formal request to the ESA Director of Science and Robotic Exploration (D/SRE) or the appropriate Russian authorities. The relevant LFA, in consultation with the resigning PI, will provide a proposal for a replacement of the PI role. The D/SRE (or the Russian authorities) will evaluate the proposal and will appoint a new PI in agreement with the Lead Funding Agency.

9. Communications and Public Outreach:

   Support ESA, Roscosmos, and LFA science communications and public outreach activities for the ExoMars missions. Provide suitable information and data in a timely manner, as defined in the Science Communications Plan (SCP).

   a. Support the reporting, by ESA and Roscosmos on the web, of the ExoMars missions' science activities and results.

3.1.2 Co-Principal Investigator

Co-Principal Investigators are responsible for their own funding, which is guaranteed via their national funding agencies and must be underwritten by formal interagency agreements with the LFA representing the PI. The instrument's Lead Funding Agency holds overall financial responsibility with respect to instrument development and delivery to ESA.

The Co-Principal Investigator assists the Principal Investigator and is responsible for the execution and delivery of his/her contribution to the instrument project.

All ESA and Roscosmos communications to the instrument team members are addressed to both the PI and Co-PI, who are then to distribute them to the rest of the team, coordinating the execution of any required actions.

3.1.3 Co-Investigators

The experts forming part of a science team providing an instrument are Co-Investigators. Each Co-Investigator must have a well-defined role with regard to the contribution of hardware, software, scientific support, or expertise within the instrument consortium. These roles and qualifications will be identified and recorded in the relevant E-ICD. PIs may review the status of their team's composition regularly and implement changes if required. Any modifications will be promptly communicated to ESA and to the instrument's Lead Funding Agency. The Lead Funding Agency, however, will not change during the development of the instrument.

Co-Investigators are responsible for obtaining their own funding, which must be guaranteed by their respective national funding agencies, and which is formally underwritten with the Lead Funding Agency (holding overall financial responsibility with respect to the instrument development and its delivery to ESA) in the Instrument Multilateral Agreement (IMA).

3.1.4 Interdisciplinary Scientists

Interdisciplinary Scientists (IDS) will be selected through dedicated Announcements of Opportunity (AOs) once the final configuration and payload composition of each mission are well consolidated—typically one or two years before launch. ESA will involve the PB-HME and SPC accordingly. It is foreseen to appoint up to two IDSs for the ExoMars 2016 mission and up to five IDSs for the ExoMars 2018 mission. The IDS appointments will be for a term equal to the nominal lifetime of the mission element, with a maximum possible duration of 5 years (TBC). As a general rule, Co-Is from instrument teams may apply to become IDSs, where PIs and Co-PIs are excluded.

The added value of IDSs is that their efforts are devoted to scientific cross-fertilisation. Thus, IDSs will be encouraged to take part in the analysis of data from different instruments on board one or more elements of a mission for pursuing interdisciplinary objectives not already covered by the scientific objectives of the selected instruments. The scientific objectives associated with the IDSs' tasks will not compete with the selected instruments' scientific objectives.

IDSs will have the same access and data rights as PIs supporting the development of ExoMars instruments. IDSs will be expected to provide support to the science communications activities of ESA and to the instrument teams.

Individual scientists, possibly supported by a team, can apply for IDS positions. The IDS candidates must present clearly their scientific case, the relevance of their contribution to the overall mission science, and the instrument data sets needed to carry out their research programme. The proposals must also demonstrate the financial endorsement of the respective national funding agencies or supporting institution.

3.1.5 Guest Investigators

Guest Investigators (GI) are individual scientists wishing to make use of the data collected by one or more instruments, in combination with results from other missions, ground observations, laboratory measurements, or numerical models. The purpose of GIs is to spread the use of, and complement, ExoMars data more widely in the planetary science community.

The GI proposals must be submitted to ESA following an open AO process. ESA will involve the PB-HME and SPC accordingly. The proposers shall agree their investigation's tasks with the relevant instrument(s) PIs, with the concurrence of the ESA Project Scientist. GIs will typically be selected after launch. They are expected to participate to the mission's activities and have access to data only through the PIs they are associated with. They are normally invited to take part in specific ExoMars Science Working Team (ESWT) activities and science communications releases.

GIs will be typically appointed for the nominal duration of the mission element, renewable in case of an extended mission—to be determined on a case-by-case basis. Should the GIs require funding for their work, they should secure them with their national funding agency, or with other research support institutions.

4 SELECTION PROCESS

The ExoMars Programme has had a long evolution (please refer to Annex 3). Payloads for the following three mission elements have been selected following an open, competitive, peer-review process: the Rover, the TGO, and the EDM. An AO for Surface Platform instruments is planned for release.

4.1 ExoMars Rover Payload Selection Process

For the ExoMars Rover mission the Lead Funding Agencies responsible for developing instruments as "national contribution" are required to sign an Instrument Multilateral Agreement (IMA). However, Roscosmos payload contributions will be governed by the relevant ESA-Roscosmos agreements.

4.1.1 Rover Payload Reviews and Evolution

The Rover instruments have so far undergone three independent, international peer assessments for which the ESA advisory structure was consulted: In 2003, in response to a first Call[1]; in 2007 for the Payload Confirmation Review (PCR)[2]; and in 2009 for the final Payload Confirmation Review #2 (PCR2)[3]. The latter two exercises became necessary due to changes in the mission scenario and in the resources available for the Pasteur payload.

The 2009 PCR2 panel identified five possible payload configurations addressing the Rover mission's scientific objectives, spanning the mass range 16.7 to 12.3 kg (called Options A–E respectively), with correspondingly decreasing science capabilities. The panel also underlined the need to preserve the 2.0-m depth reach in the drill, for scientific reliability reasons.

On the basis of the Rover mass that the mission configuration being considered at the time could accommodate, the ExoMars Project proposed to implement Option D. Option D included seven instruments (PanCam, WISDOM, Ma_MISS, MicrOmega IR, Raman, MOMA, and MARS-XRD). The Programme Board (PB-HME) accepted this, but recommended to the project exploring possibilities to reinforce the exobiology content of the Rover mission.

A few months after the completion of the PCR2, an important change took place in ExoMars. ESA and NASA agreed to pursue a collaborative programme for the exploration of Mars, with missions in 2016 and 2018. Since the NASA-ESA 2018 mission scenario could accommodate a slightly larger ExoMars Rover, the Project Team evaluated the possibility to embark additional instruments, in line with the PCR2 identified payload options.

The next payload option up, Option C, included the robotic arm. Among these instruments, the PCR2 panel judged the CLose-UP Imager (CLUPI) "essential for achieving the mission's scientific objectives." CLUPI can provide much needed, high-resolution imaging capabilities (20-µm resolution) to study the depositional environment, and potential morphological signatures of past biological activity preserved on the texture of surface rocks. This is a function that exceeds the possibilities of the PanCam camera system.

Even though it proved ultimately impossible to implement the robotic arm, an alternative way was found for CLUPI, attaching the instrument to the drill box, thus reinforcing the Rover's exobiology capabilities.

Another exobiology instrument considered by the PCR2 panel was the Life Marker Chip (LMC). LMC can perform liquid extraction of organic molecules from the sample material collected by the drill. LMC allows

[1] ExoMars Call for Ideas, Pasteur Instrument Payload for the ExoMars Rover Mission, Ref. CI-Pasteur-2003, 14 February 2003.

[2] Payload Confirmation Review (PCR) Board report, Ref. EXM-MS-PL-ESA-00005, Issue 1, 28 March 2007.

[3] Payload Confirmation Review #2 (PCR2) Review report, Ref. EXM-PL-REP-ESA-00028, Issue 1, 3 April 2009.

detecting simultaneously multiple molecular biomarkers and non-biogenic organic molecules employing specific antibodies in a microarray inhibition/competition immunoassay. The PCR2 review panel concluded that "the LMC concept provides a promising approach for astrobiology research, its aims are innovative, and the results could be fascinating." However, it also found that the instrument had not then reached a sufficient technology readiness level, particularly concerning the state of development of functional antibodies and their stability under mission conditions. The PCR2 panel recommended that LMC be developed further and considered for a Mars mission after 2016. The postponement of the ExoMars Rover launch to 2018 was deemed to enable LMC to be included in the Pasteur payload.

Summarising, by mid 2010, nine instruments were considered selected for the ExoMars Rover mission: PanCam, CLUPI, WISDOM, Ma_MISS, MicrOmega IR, RLS, MARS-XRD, MOMA, and LMC.

In January 2012, NASA announced to ESA and Roscosmos that they would no longer be able to participate as a major partner. Following a rapid technical evaluation, ESA and Roscosmos confirmed their interest in studying a joint implementation of ExoMars. This, however, meant going back to the 300-kg-class European Rover design, which was smaller than the 900-kg, MSL-based concept considered during the latter stages of the ESA-NASA cooperation. Whereas it was feasible to include two relatively small Russian instruments on the Rover mast and body, it was no longer possible to accommodate all Analytical Laboratory Drawer (ALD) instruments, mainly because of ALD volume constraints, but also overall Rover mass limitations.

On 23 April 2012, the approach to find a solution for the ALD was discussed with the Rover Instrument Steering Committee (RISC), including Lead Funding Agency (LFA) members signatory to the ExoMars Rover Instrument Multilateral Agreement (IMA). Based on the available Rover resources and on the scientific recommendations of the PCR2 panel, ESA produced two possible ALD payload options. The Executive then requested advice to the Solar System and Exploration Working Group (SSEWG), and to the Human Spaceflight and Exploration Science Advisory Committee (HESAC), on which ALD payload option to retain. Based on these inputs, on 11 July 2012 the Programme Board (PB-HME) approved a revised ALD payload configuration without MARS-XRD and LMC [Ref. ESA/PB-HME(2012)35].

The confirmed Rover Pasteur payload includes the following nine instruments: PanCam, ISEM, WISDOM, ADRON, CLUPI, Ma_MISS, MicrOmega, RLS, and MOMA.

4.1.2 Rover Instrument Multilateral Agreement (IMA)

The purpose of the Rover IMA is to record the commitment of the Lead Funding Agencies to define their respective rights and obligations, and to organise the management of the Instrument Projects.

The Lead Funding Agencies agree to cooperate pursuant to the terms of the Rover IMA in order to execute and fulfil the tasks necessary to design, develop, manufacture, and deliver to ESA specific instruments for integration in the ExoMars Rover mission.

The Roscosmos payload contributions are agreed and governed by the relevant ESA-Roscosmos agreements.

The Programme Board (PB-HME) approved the revised version of the (already signed, 20 April 2011) Rover IMA, confirming the latest composition of the ExoMars Rover's Pasteur payload, on 5 February 2013 [Ref. PB-HME(2013)1].

4.1.2.1 Rover Instrument Steering Committee (RISC)

As defined in the Rover IMA, the RISC groups all Lead Funding Agencies providing instruments for the ExoMars Rover. The RISC is the forum that oversees the timely fulfilment of the obligations concerning all parties to the IMA. Each Lead Funding Agency nominates one representative. The ESA Project Manager, Project Scientist, and Payload Manager also attend RISC meetings. In consultation with the ExoMars Project Manager, the RISC Chair typically convenes meetings once a year, though additional meetings can also be requested by any of the parties.

4.2 ExoMars TGO and EDM Payload Selection Process

The Lead Funding Agencies developing instruments as "national contribution" for the ExoMars 2016 TGO and EDM mission are required to sign an Instrument Agreement. However, Roscosmos payload contributions will be governed by the relevant ESA-Roscosmos agreements.

4.2.1 TGO Payload Review and Evolution

ESA and NASA released a joint AO for TGO instruments on 15 January 2010. Proposals were received on 15 April 2010. During May and June 2010 the two agencies conducted a joint evaluation and coordinated selection process, leading to a mutually agreed payload. The SSEWG endorsed the recommended payload during its meeting on 29 June 2010. The Programme Board (PB-HME) approved the TGO payload by a written procedure completed on 20 August 2010 [Ref. ESA/PB-HME(2010)52, rev.2].

At the time the TGO instrument complement included one European (NOMAD) and four US instruments (MATMOS, EMCS, MAGIE, and HiSCI). MATMOS was a sun-occultation trace gas identifier. NOMAD would also work in sun occultation mode, but would in addition include nadir and limb observing modes, allowing it to perform mapping of trace gases over the martian surface. EMCS would provide basic atmospheric state parameters, such as pressure, temperature, dust, and ice aerosol content. MAGIE was a wide-angle camera to observe cloud circulation patterns. Finally, HiSCI would obtain high-resolution, colour, stereo image pairs. The TGO selected payload would constitute a very powerful set of tools for studying atmospheric trace components.

In 2012, when NASA withdrew from the cooperative programme, they also halted their TGO instrument development activities. By then, ESA and Roscosmos had already initiated a dialogue. In order to achieve the 2016 mission launch, it was crucial that a new set of instruments be identified as a matter of urgency.

NOMAD would allow fulfilling the exploration of atmospheric trace gases objective. With some hardware modifications, the erstwhile HiSCI camera would evolve into CaSSIS. Roscosmos had two instruments in an advanced state of development: The Atmospheric Chemistry Suite (ACS), a cluster of infrared spectrometers to investigate atmospheric chemistry and structure; and the Fine Resolution Epithermal Neutron Detector (FREND), to map the presence of hydrogen in the martian subsurface, targeting deposits of buried water ice and hydrated minerals.

Following the signature of the ESA-Roscosmos agreement for the implementation of the ExoMars Programme on 14 March 2013, the partners have confirmed the payload for the ExoMars TGO mission. It consists of four instruments: NOMAD, ACS, FREND, and CaSSIS.

4.2.2 EDM Payload Review and Evolution

ESA and NASA issued a joint AO for EDM investigations on 30 November 2010. Since the EDM would be a technology demonstrator with limited surface life, the EDM AO requested proposals either for a complete payload, or for sensors to be accommodated as part of a complete payload. The AO also requested proposals to conduct scientific analyses using the data acquired by the EDM engineering sensors during the entry and descent phases.

Proposals were received on 1 March 2011. During March and April 2011 the two agencies conducted a joint evaluation and coordinated selection process, leading to a mutually agreed outcome. The SSEWG endorsed the recommended experiments during its meeting on 5 May 2011. The Programme Board (PB-HME) approved the DREAMS surface payload and the AMELIA entry and descent science investigation on 26 May 2011 [Ref. ESA/PB-HME(2011)40].

Initially DREAMS included the following sensors: MetWind, for wind measurements; MetHumi, for humidity; MetBaro, for pressure; MarsTem, for temperature; ODS, for optical opacity; and MicroARES, for atmospheric electrical charging. However, during 2012, lack of support by the ODS LFA resulted in the replacement of ODS by SIS, a sensor that can provide similar data.

4.2.3 ExoMars 2016 Instrument Agreement

A dedicated agreement between ESA and the Agenzia Spaziale Italiana (ASI) governs the provision of the DREAMS and AMELIA investigations for the ExoMars 2016 EDM. The two European TGO instruments, NOMAD and CaSSIS are implemented through ESA's PRODEX programme. Roscosmos payload contributions are agreed and governed by the relevant ESA-Roscosmos agreements.

The Programme Board (PB-HME) approved the ExoMars 2016 instrument agreement (for DREAMS and AMELIA) on 6 May 2013, after which it was signed on 9 September 2013 [Ref. ESA/PB-HME(2013)27].

4.3 ExoMars Surface Platform Payload Selection Process

European contributions to the science payload for the ExoMars Surface Platform (SP), in addition to any Roscosmos provided instruments, will be selected in response to a competitive Announcement of Opportunity (AO) jointly organised by Roscosmos and ESA. The AO will request the provision of instruments or instrument elements lead by scientists based in ESA member states and nationally funded.

Instrument proposals will have to be compatible with the SP scientific and operational objectives, as well as with the available spacecraft resources. This information will be made available to potential proposers in a dedicated Experiment-Proposal Information Package (E-PIP) to accompany the main AO document.

Each proposal for an instrument must identify a single PI heading the instrument consortium. The PI must receive full financial support from the national funding agency of his/her country, hereafter referred to as Lead Funding Agency (LFA) for the instrument. In some instances, various organisations or institutions may contribute resources for the instrument project; in all cases, it will be the LFA representing the instrument consortium vis-à-vis ESA and Roscosmos. The LFA is expected to provide the major portion of the instrument's funding and have prime science and industrial responsibility in the instrument's development and exploitation. The LFA must be in a position to deliver all instrument models according to the need dates specified by the Roscosmos/ESA Project Team in the call.

Instrument proposals will have to include Letters of Endorsement (LOE) from each participating funding agency, collectively committing to fund the entire instrument development, as well as its operation, data reduction, and product submission to the appropriate planetary science archives. In its LOE, the instrument LFA will summarise the contributions from all instrument partners, will commit to fund on behalf of the consortium, and will include a financial deployment table with the estimated milestones until end of project. This LOE will constitute a preliminary agreement between the LFA and ESA/Roscosmos until an Instrument Multilateral Agreement (IMA) between all participating LFAs can be formalised.

4.3.1 Payload Review Committee

Roscosmos and ESA will appoint an international Payload Review Committee (PRC) formed by independent scientists to assess all instrument proposals received in response to the AO according to the following terms of reference:

- Verify whether all science objectives are addressed within the overall AO response;
- Evaluate each instrument proposal to determine if it can achieve the requested science requirements in terms of measurement sensitivity, resolution, range, etc., as specified in the call's documents, to fulfil the science objectives;
- Ensure compatibility of each instrument against the objectives of the model payload as defined in the call's documents;
- In cases where competing instrument proposals would be submitted, recommend which proposal(s) should be selected;
- Identify clear alternatives among the proposed instruments in case of too high development risk and/or incompatibility with available spacecraft resources or interfaces;

The Payload Review Committee will work in close collaboration with the internal Roscosmos and ESA review teams, consisting of selected Agency personnel, its industrial contractors, as well as invited specialists. For each instrument proposal, ESA and Roscosmos will consult extensively with funding agencies and provide, via the appropriate internal review teams, the PRC with input on implementation feasibility and risk assessment.

A “No Conflict of Interest” rule will apply. No potential PI, Co-PI, or Team Member for any instrument proposal can be a member of the PRC, nor be involved in the selection procedure.

4.3.2 Evaluation Criteria

The PRC evaluate each instrument proposal using the following preliminary criteria:

- Relevance of the instrument proposal to the mission’s scientific objectives.
- Adequacy of the instrument measurements to address the mission’s objectives.
- Likelihood of the instrument to provide the required measurement performance.
- Feasibility and heritage of the proposed instrument.
- Instrument development status.
- Availability of technologies required by the instrument. In case new technologies are required, assessment of their development status. Any ITAR-related approval aspects must be identified in the proposal.
- Compliance with the spacecraft interfaces.
- Credibility of the instrument’s development plan and test and validation programme.
- Compatibility of the instrument with the Mars surface environment, mission constraints, and spacecraft resources.
- Assessment of the instrument’s operational complexity.
- Quality of the data analysis plan.
- Adequacy of the management plan in relation to the instrument’s complexity, both technical and/or arising from managing element/institution interfaces within the instrument consortium.
- Assessment of compliance with applicable planetary protection rules.
- Continuity of human and institutional resources to ensure a timely execution of the instrument project, including development, construction, calibration, operation, data analysis and publication, and provision of results to the Agency science archives. ESA and Roscosmos will undertake the analysis of manpower funding profiles for all mission phases; including science exploitation, publication, and archiving; for each science institute within the instrument consortium, verifying that they are covered by the appropriate funding agency and confirmed by the instrument’s Lead Funding Agency.
- Competence and experience of the instrument team in all relevant areas (science, technology, software, management, etc.).
- Credibility of costing. This will be assessed by ESA staff experienced in instrument cost analysis, in coordination with the proposal’s LFA and other relevant funding agencies.
- Compliance with ESA applicable management, engineering, reporting, and product assurance requirements and standards.
- Assessment of the possible financial impact of the proposed instrument upon ESA.
- Verification of the commitment of all national funding agencies to adequately support member institutes within the instrument consortium under the overall responsibility of the Lead Funding Agency.
- Commitment of the Principal Investigator’s funding agency to become the Lead Funding Agency and provision and completeness of the LOE.

4.3.3 Evaluation Process

Scientific Evaluation:
The PRC will evaluate the scientific merits of each instrument proposal and its relevance to the mission objectives according to the terms of reference specified above.

Technical, Managerial, and Financial Evaluation:
Roscosmos and ESA will put together a technical review panel to assess all instrument proposals' managerial and technical compliance with the mission requirements. The instrument concept, feasibility, management approach, and proposed funding scheme will be also scrutinised. If deemed necessary, proposal PIs and Co-Is may be invited for clarification meetings to discuss technical, managerial, or financial issues.

Final Recommendation
Based on the technical and scientific assessment of each instrument proposal and on the SP accommodation assessment, the PRC will recommend a configuration for the ExoMars SP payload that satisfies the mission's scientific objectives within the available resource envelope.

The recommendation of the PRC will be delivered to ESA's Director of Science and Robotic Exploration and the appropriate Russian authorities. Roscosmos and ESA will present the PRC recommendation to their Advisory Bodies for endorsement (for ESA: SSEWG, SSAC, and HESAC). Thereafter, the Agencies will elaborate a proposal to be submitted for evaluation and approval to their Governing Bodies (for ESA: the Programme Board (PB-HME) and the SPC).

4.4 Instrument Deselection Policy

The following Deselection Policy will apply for the entire implementation phase of ExoMars Programme missions following the completion of the relevant payload confirmation process. The reasons that could lead to the deselection of an instrument are:

1. Resource insufficiency: For example, available mass or volume for instruments. This possibility may arise as a result of a more-accurate technical estimate performed by Industry. In such cases, ESA will endeavour to define alternatives that may solve the problem whilst minimising the consequences for the mission's science return. In case a satisfactory solution cannot be found at project level, ESA will organise a dedicated ExoMars Science Working Team (ESWT) meeting to consider the situation for the payload as a whole. All major payload decisions will be taken in consultation with the ExoMars science community and ESA's Advisory Bodies (as independent reviewers).

2. Instrument exceeds allocated resources: For example, an instrument's mass is greater than that agreed. This is considered a grave problem. The Instrument Project has the obligation to inform ESA early of any such instances. ESA will do its outmost to assist them in the search for a viable solution. In case this is not possible, ESA will evaluate the risk to the mission and may recommend deselecting the instrument. The decision leading to this recommendation will be taken in consultation with the ExoMars science community and ESA's Advisory Bodies.

3. Instrument funding insufficiency: At the time of signature of the IMA, each Lead Funding Agencies commits to timely provide the necessary resources to bring its respective Instrument Project to a successful completion. In case a funding agency were to break its contract, for whatever reason, the following mechanism will be put in effect:

    a. Evaluation of the effect of deselecting the instrument in consultation with the RISC (when applicable) and the ESA Advisory Bodies.

    b. In case the Lead Funding Agency does not have the financial capability to comply with its IMA commitments, ESA may likely recommend that the instrument be deselected.

4. Likelihood that instrument may not be available in time: ESA will closely monitor the progress of all ExoMars Instrument Projects. In case substantial delays were to occur, they would constitute a breach of the commitments undertaken in the IMA. If the Agency judges that the delays put at risk the mission launch date, ESA will recommend that the instrument be deselected.

5. Instrument technical or scientific underperformance: All instruments must be able to timely and reliably demonstrate appropriate technical and scientific performance to be included in the mission. If ever underperformance problems were to occur, the Instrument Project has the obligation to inform ESA early of such instances. ESA will do its outmost to assist them in the search for a viable solution. In case this is not possible, ESA will evaluate the risk to the mission—programmatic, technical, and scientific—and may recommend deselecting the instrument. The decision leading to this recommendation will be taken in consultation with the ExoMars science community and ESA's Advisory Bodies.

In case of problems affecting one or more Rover instruments, ESA will conduct consultations with the Rover Instrument Steering Committee (RISC) to try to identify possible solution.

The final decision for deselecting an instrument will be taken by the Programme Board (PB-HME) and SPC, based on the recommendations of ESA and its Advisory Bodies (SSEWG, SSAC, and HESAC).

4.5 Selection of Interdisciplinary Scientists

ESA and Roscosmos will organise a competitive peer review process involving independent international scientists. This Call will be open to scientists based in ESA Member States, Canada, and Russia. However, specific expertise not present in ESA Member States, Canada and Russia could be covered by scientists from other countries. Following the evaluation of the IDS proposals, the Agencies will present the recommended IDS list to their Advisory Bodies for endorsement (for ESA: SSEWG, SSAC, and HESAC), and to their Governing Bodies for approval (for ESA: the Programme Board (PB-HME) and the SPC).

4.6 Selection of Guest Investigators

ESA and Roscosmos will organise an open, competitive peer review process involving independent international scientists. The selection criteria for GIs will be established in consultation with the ESWT. Following the evaluation of the GI proposals, the Agencies will present the recommended GI list to their Advisory Bodies for endorsement (for ESA: SSEWG, SSAC, and HESAC), and to their Governing Bodies for approval (for ESA: the Programme Board (PB-HME) and the SPC).

5 SCIENCE MANAGEMENT

5.1 The Project Scientists

ESA and Roscosmos appoint one ExoMars Project Scientist (PS) each. These PSs are responsible for the Programme's overall scientific coordination, and constitute ESA and Roscosmos' interface with the ExoMars science community. The two PSs will co-chair the ExoMars Science Working Team (ESWT) and coordinate its activities (the role of the ESWT is described in the next section). Dedicated PSs will also be appointed (as needed) for each of the ExoMars Programme's four mission elements (see Fig. 1).

During all mission phases, from the beginning of the implementation phase until the end of the exploitation phase, the PSs will be responsible for all scientific issues within the Project. The PSs will advise the ESA and Roscosmos PMs on technical matters affecting scientific performance. In particular, the PSs will participate to the critical analysis of hardware design, performance, and operations with the objective to verify that the missions' scientific objectives can be fulfilled. It is also the PSs' responsibility to monitor the state of implementation and readiness of the instruments' operations and data processing systems.

The PSs will coordinate the scientific community's participation and support to milestone reviews during the project development phase. The PSs will organise meetings with the scientific community to assist on project development issues that may impact the missions' science return; for example, in case reduction of an instrument's mass would become necessary. The PSs, in cooperation with the ESWT, may also establish *ad hoc* working groups to address specific mission aspects requiring consultation with the scientific community; for example, to propose a list of candidate landing sites and to participate in its down selection process.

After a mission's commissioning phase, the PSs will continue their activity as the main interface with the scientific community and the main scientific interface with the MOC, SOC, ROCC, and SPOCC.

The PSs will coordinate the creation of the scientific products, and will monitor their archiving and distribution to the scientific community. The PSs will encourage an orderly, prompt, and fair implementation of the mission's data exploitation phase. The PSs will foster the utilisation of the TGO, Rover, and SP payloads in an integral and holistic manner, facilitating the cooperation among scientists with a view to maximising the ExoMars Programme's science return and promptly publish its results.

5.2 The ExoMars Science Working Team and its Structure

The ESWT ensures the scientific coordination across all ExoMars mission elements. The ESWT includes all instrument PIs and Co-PIs, as well as the IDSs. Additional participants may be invited to join at the ESWT members' discretion. Two ExoMars PSs (one from ESA, one from Roscosmos) chair the ESWT. This body will exist throughout the mission's lifetime.

Dedicated science working teams will be created for each of the ExoMars Programme's four mission elements: TGO SWT, EDM SWT, Rover SWT, and SP SWT—referred to as Mission Science Working Teams (MSWTs). The dedicated PSs (appointed by ESA and Roscosmos as needed) chair the MSWTs (see Fig. 1).

The ESWT will monitor and advice ESA and Roscosmos on all aspects of ExoMars missions that may have an effect on their scientific performance. The ESWT will assist the PSs to maximise the ExoMars missions' scientific return within the established project and operations boundary conditions.

The ESWT represents all other team members. The ESWT will work in a spirit of cooperation and openness, and will have the overall scientific success of ExoMars as its overarching objective. The ESWT will aim to make recommendations based on consensus, but if ever voting were to become necessary, each PI will have one vote.

The MSWTs will ensure the scientific coordination in the respective mission. The PSs will monitor the detailed technical implementation of scientific requirements, the verification and testing of mission science elements and functions, whether under the responsibility of ESA or Roscosmos. The PSs of the MSWTs will inform the ESWT of their findings and recommendations (please see Fig. 1).

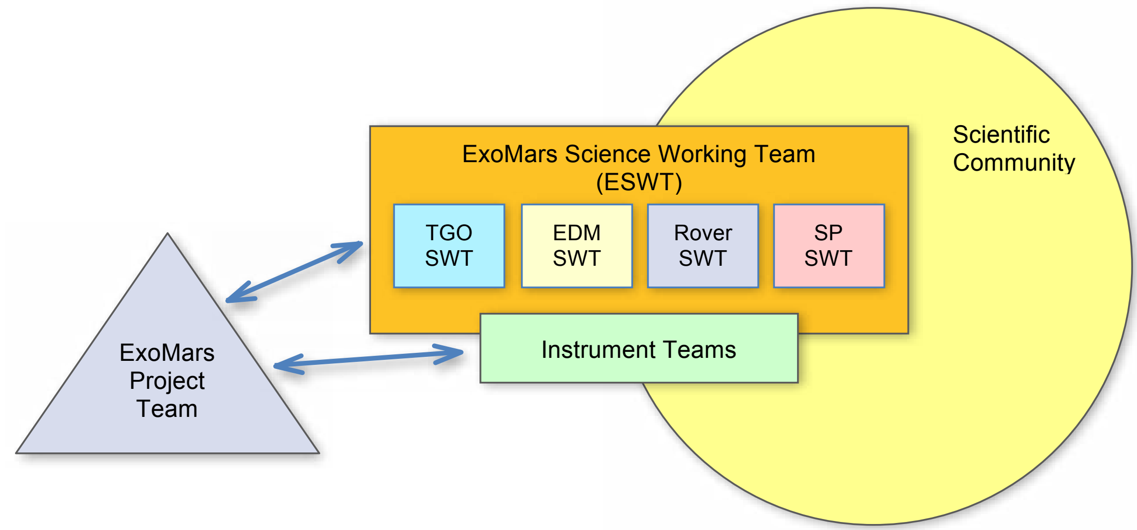

Fig. 1: The ExoMars Science Working Team (ESWT) advises ESA and Roscosmos on all aspects of ExoMars that may have an effect on scientific performance. The ESWT represents all instrument and IDSs. It includes mission-specific science working teams for each of the programme's four mission elements: TGO, EDM, Rover, and SP.

All SWT members are expected to rely on their own funding to participate in SWT meetings.

More specifically, the ESWT and MSWTs (within their respective roles) will:

- Advice ESA on all scientific aspects of the development and operation of the ExoMars missions.
- Contribute to establishing a baseline operations scenario to fulfil the ExoMars Programme's scientific objectives.
- Indicate members (typically PIs) to participate in major ExoMars project reviews, or as requested by the PSs and PMs.
- Perform specific tasks, as needed, during the development of the project.

The ESWT and MSWTs will review the tasks and activities of the Rover Operations Control Centre (ROCC) and of the TGO and SP Science Operations Control Centre (SPOCC) to:

- Optimise the ExoMars Programme's science return from a science operations point of view.
- Advise on the development of the science ground segment, with particular emphasis on the Rover and SP operations scenario, software, ancillary data products, and the science database and archive.

5.3 The Project Team

ESA and Roscosmos nominate each an ExoMars Project Manager (PM). The Roscosmos Project Team is distributed among a number of designated entities, with the Lavochkin Association as the lead. They include the Lavochkin Association (spacecraft development), Krunichev State Research and Production Space Centre (launchers), TsENKI (launch services at Baikonur), TsNIIMASH (management, scientific, and engineering support), and IKI (scientific payload).

This joint ExoMars Project Team will be responsible for the development and implementation of all mission elements. The ExoMars PMs head their respective Project Teams, which have mutually agreed mission tasks. The PMs will fulfil this function until the completion of each mission's commissioning phase.

Following the completion of the 2016 mission's commissioning phase, the TGO Mission Manager (MM) will assume the responsibility for the science exploration phase of the ExoMars Orbiter. Similarly, upon completion of the Rover and SP commissioning phases, the Rover MM and the Surface Platform MM will become responsible, respectively, for the Rover and the SP's surface science phase.

ESA and Roscosmos, via the Project Managers, and later the Mission Managers, will retain the overall responsibility for the ExoMars Programme, including all its elements, through all phases.

5.4 Monitoring of Instrument Development

- For ESA-provided instrument platforms (TGO, EDM, Rover):

  The ESA Project Manager, in close cooperation with the PSs, will monitor the general progress of the design, development, and verification of instruments with special emphasis on the management of interfaces and their compliance. Instrument teams will have to demonstrate to ESA, in regular reports and during formal reviews, compliance with the ExoMars scientific objectives, the applicable spacecraft system constraints, including Planetary Protection requirements, the spacecraft interfaces, and the programme's schedule, as defined in the mutually agreed instrument E-ICDs. Failure to timely or satisfactorily achieve this may result in the deselection of an instrument, according to the rules defined in this document.

  The ESA Project Team is not responsible for supporting the development of tools/services in the instrument teams' institutes for conducting scientific analysis of their instrument's data.

- For the Roscosmos-provided Surface platform (SP):

  A reciprocal set of responsibilities and obligations, as identified above, will apply for any European contributions to the SP payload.

5.5 Selection of Landing Sites

5.5.1 EDM Landing Site

The 2016 EDM is mainly a technology demonstration mission, whose DREAMS payload is devoted to the study of the martian surface environment. Thus, the EDM science is not location-specific. For this reason, the EDM landing site has been selected on the basis of landing safety and maximising surface lifetime.

A suitable landing ellipse (100 km x 15 km) has been identified in the Meridiani Planum region (1.82º S, 6.15º W), north of where the Opportunity rover landed in 2004. This is a well-characterised area, known to be mostly flat and free of rocks. A landing site certification campaign is being conducted by ESA, with the cooperation on NASA, JPL, the Mars Express (MEX), and the Mars Reconnaissance Orbiter (MRO) science teams.

5.5.2 Rover and Surface Platform Landing Site

The 2018 mission will deliver the ExoMars Rover and Surface Platform (SP) to Mars.

5.5.2.1 Engineering and Science Constraints

The certification of one or more landing sites for the 2018 ExoMars mission will require the detailed assessment of each site's compliance with a large number of engineering constraints. This is a long and laborious process for which especially targeted remote sensing observations (e.g. MEX and MRO imaging and spectral data sets) must be obtained and analysed, typically necessitating several years to accomplish.

Examples of important landing site engineering constraints include:

- Latitude band and time of the year, for electrical power generation with solar arrays;
- Landing ellipse size and azimuth: A Monte Carlo simulation is used to compute the probable dispersion area around the desired landing location. These unwanted deviations result from unavoidable navigation and atmospheric uncertainties. The smaller the landing ellipse, the easier it becomes to find a suitable landing location.
- Maximum allowable elevation, to have sufficient atmosphere for the parachutes to slow the descent;
- Maximum horizontal wind speed, shear, and turbulence in the last few kilometres to minimise horizontal velocity at touchdown;
- Maximum rock abundance: Site must be safe for landing and for Rover traverse operations.
- Maximum slopes at various scales: Limitation necessary for the descent radar to operate properly.
- Minimum thermal inertia: Thermal inertia must be high to ensure a radar-reflective, load-bearing surface not dominated by fine-grained dust—safe for landing and for Rover traverse operations.

The scientific evaluation of candidate sites will require the detailed examination of subtle morphological clues (e.g. putative water-related structures) and spectroscopic signatures associated with past, long lasting aqueous environments. It will also involve the geologic mapping and dating of units in each candidate location. The latter is necessary to try to establish the candidate site's depositional history. Only once all this important information has become available can the science community assess the likelihood that the proposed site can meet the mission's science objectives.

Summarising, before a landing site can be considered “mission certified” it is necessary to carry out two types of verification: 1) Prove that the DM would be able to land safely there (with a high probability); and 2) Establish that the Rover and SP would be able to achieve their science objectives (with a high probability). Among these two, landing safely must receive a higher priority, as without a successful landing there will be no science.

5.5.2.2 Landing Site Selection Process

ESA and Roscosmos have released a *Call for Letters of Application for Membership in the 2018 Landing Site Selection Working Group (LSSWG)*. The responses were competitively screened based on the scientific expertise required to help with the mission's landing site activities. The LSSWG was appointed in December 2013 and includes recognised, international science experts, as well as representatives from the ESWT, the ExoMars PSs and members from the ExoMars Project and Industry teams.

On 17 December 2013, ESA and Roscosmos have issued a first open call to propose landing sites suitable for accomplishing the 2018 ExoMars mission's scientific objectives. The call included information on applicable engineering and planetary protection constraints that the sites must satisfy. Proposers were requested to take these into account. The LSSWG will carry out a preliminary screening of the proposals.

Next, the LSSWG will organise an open scientific workshop to discuss each of the landing site proposals considered viable. In case problems would be identified with any of the sites, the LSSWG will contact the proposers prior to the workshop, either to request they address specific concerns, or to inform them that the site can no longer be considered. The result of the workshop will form the basis for prioritising and narrowing down the list of candidate landing sites.

After the workshop, the LSSWG will commence a more detailed analysis of the various candidate sites in the list. The goal will be to assess, as much as possible, whether they are compatible with the applicable engineering, science, and planetary protection constraints.

Other landing site workshops will follow at regular intervals, typically once a year. A desirable goal would be to complete the certification of a suitable (science, engineering, and planetary protection) landing site by the mission's Critical Design Review (CDR).

The landing site(s) recommendation for the 2018 mission will be produced by the LSSWG. This recommendation will be delivered to ESA's Director of Science and Robotic Exploration and the appropriate Russian authorities. Roscosmos and ESA will present the landing site(s) recommendation to their Advisory Bodies for endorsement (for ESA: SSEWG, SSAC, and HESAC). Thereafter, the Agencies will elaborate a proposal to be submitted for evaluation and approval to their Governing Bodies (for ESA: the Programme Board (PB-HME) and the SPC).

6 OPERATIONS AND DATA

6.1 ExoMars Operations Concept

6.1.1 2016 Mission

ESA will establish the 2016 ExoMars Mission Operations Centre (MOC) in ESOC.

Roscosmos will be responsible for the 2016 mission launch. ESA will undertake checkout and operations of the spacecraft. ESA will also be in charge of operations, data acquisition, data transmission, and distribution for the TGO and EDM.

ESA will establish a 2016 ExoMars TGO Science Operations Centre (SOC) in ESAC, which will also be responsible for archiving and providing access to the ExoMars 2016 science products. The mission's data archive will be in ESAC. A copy of this data archive will also be available at IKI (Russia).

The ESWT will propose the payload science operations timeline for the ExoMars TGO and EDM missions. However, under the authority of the MM, ESA will verify that the recommended operations timeline is compatible with the spacecraft available resources.

Programming of the timeline and telemetry monitoring of EDM instruments will be the responsibility of ESOC through coordination with the ESA responsible groups.

6.1.2 2018 Mission

ESA will establish the 2018 ExoMars MOC in ESOC.

Roscosmos will be responsible for the 2018 mission launch. ESA will undertake checkout and operations of the spacecraft until touchdown. Once on the surface of Mars, ESA will control the Rover and Roscosmos will control the Surface Platform (SP).

ESA will set up a Rover Operations Control Centre (ROCC) at ALTEC, in Turin (I), to control the ExoMars Rover through commands transmitted via ESOC to the ExoMars TGO, or to other communications assets, if available. The Rover scientific and housekeeping data archive will be in ESAC's PSA. A copy of the Rover data archive will also be kept in IKI (Russia).

Roscosmos will set up an SP Operations Control Centre (SPOCC) in Moscow to control the ExoMars SP through commands transmitted via ESOC to the ExoMars TGO, or to other communications assets, if available. The SP data archive will be in IKI (Russia). A copy of the SP data archive will also be maintained in ESAC.

The primary responsibility for developing the science operations strategy for the ExoMars Rover and SP missions is with the ESWT. However, under the authority of the MMs, ESA and Roscosmos will verify that the recommended operations strategy is compatible with the Rover and SP available resources. PSs and MMs will coordinate Rover, SP, and TGO operations with a view to maximise the 2018 mission's overall science return.

Once on the surface of Mars, Rover investigators will have only a few hours to process and interpret instrument data to propose a sequence of Rover activities for the next sol. To achieve this rapid-reaction scientific response it is essential to develop a critical mass of knowledgeable scientists able to promptly analyse the mission's results. For this reason, the Rover SWT will organise a Rover Tactical Task Group (RTTG), concentrating on day-to-day scientific decisions, and a Rover Strategic Task Group (RSTG), for longer-term scientific exploration planning.. These groups will include members of the Rover SWT or their teams. In case additional expertise would be required, this would be sought competitively, through an appropriate AO. These task groups, as the Rover SWT, will be granted immediate and complete access to all relevant results for the sole purpose of accomplishing their scientific planning tasks.

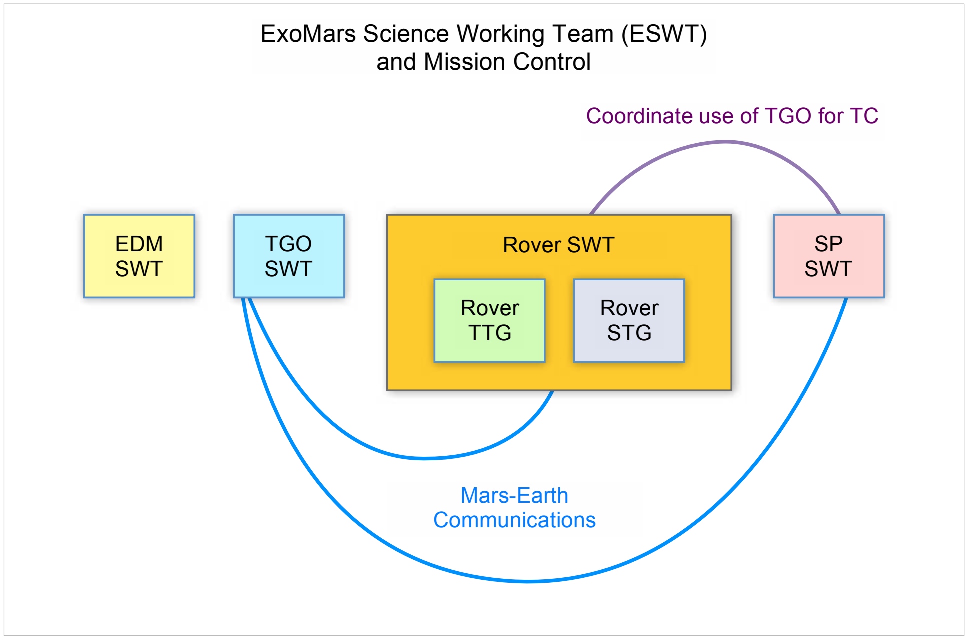

Fig. 2: The Rover SWT is in charge of defining the scientific operations that the rover must undertake to fulfil its mission. For practical reasons, two subgroups will be created, the RTTG for handling daily operations and planning, and the RSTG for preparing more long-term scientific activities. In a similar manner, the Surface Platform SWT will establish the scientific operations for the SP. The Rover, SP, and TGO Project Scientists and Mission Managers will coordinate the data bandwidth apportioning of TGO communications passes. Normally this will be done according to the expected daily needs of the Rover and the SP for the part of the mission on course. However, for special cases, such as resolving a malfunction, it will be possible to implement dedicated communications sharing protocols.

6.1.2.1 Coordination of Rover and SP Science and Communications

ESA will manage science operations for the ExoMars Rover in cooperation with Roscosmos. Roscosmos will manage science operations for the Surface Platform in cooperation with ESA.

ESA, in cooperation with Roscosmos, will coordinate science data analysis activities for the daily planning of Rover operations at the ROCC. The PS, in coordination with the ESWT and the instrument teams, will establish a Rover science operations strategy similar to that used by NASA Rover missions. This will include a Science Operations Working Team (SOWT), with subgroups having specific research foci, for short and long-term Rover operations planning.

Similarly, Roscosmos, in cooperation with ESA, will coordinate the SP science operations and data analysis.

A good dialogue and coordination between ROCC and SPOCC is fundamental since the Rover and the SP will have to share the same TGO communication passes. This is because from its 400-km altitude orbit, the TGO will see the Rover and the SP as being on the same location.

The Rover surface operations strategy requires that the ROCC tell it what to do in the morning pass, and collect the results of the Rover's work in the subsequent evening pass. Hence, most of the Rover's critical data will need to be downloaded on this evening pass. The Rover operations strategy requires, in principle, that for the nominal duration of the Rover mission, scientists must be able to analyse the received data during the martian night, while the Rover sleeps, and be ready to upload a new set of mission-validated commands early the next morning.

The SP surface operations strategy will be determined once the payload has been selected. However, if the SP carries out mainly surface and subsurface environment investigations it is likely that the instruments will collect data for several days and then make regular data dumps to Earth. It is therefore possible that the SP could use mainly morning passes for sending its data to Earth.

Being the Rover a mobile platform, it will necessarily generate a larger amount of data than the SP. There may be especially important moments when the Rover, or the SP, will require more data volume throughput—for example, in case of problem debugging. Building flexibility in the way ESA and Roscosmos manage the use of TGO communications passes is very important for the mission's overall science quality—and for operational safety too.

6.2 Mission Operations Centre

ESA will conduct all ExoMars mission operations through its Mission Operations Centre (MOC). These operations include:

- Mission planning and upload of spacecraft and payload telecommands.
- Monitoring of the spacecraft health and safety. Performing anomaly (out of limit) checks on a set of parameters (including payload) and notifying payload anomalies to the SOC and instrument teams.
- Orbit and attitude determination and control.
- On-board software maintenance and uplink of payload on-board software executable code, as generated, validated, and delivered by the instrument teams.
- Operations support for the TGO scientific instruments, commensurate with spacecraft and ground segment constraints. The individual instrument operations will be the responsibility of each specific instrument team.
- Distribution of scientific raw data, as required, e.g. TGO and EDM data to SOC, Rover data to ROCC, SP data to SPOCC.

Mission operations commence at separation of the 2016 ExoMars spacecraft from the launcher and continue until the end of the mission, when ground contact with the last spacecraft element is terminated. A similar scenario applies for the 2018 mission.

The MOC will also have the overall responsibility for planning and coordinating effective data-relay services for the ExoMars TGO, Rover, and SP. The MOC must therefore establish interfaces with the appropriate ESA and Roscosmos ground stations and SOCs. If feasible, it is envisioned to make use of NASA satellites as backup, or as a means to increase the mission's science return. In this case the MOC must also secure effective interfaces with the applicable NASA Operations Centre(s).

6.3 Science Operations Centre for the ExoMars TGO

The Science Operations Centre (SOC) will be responsible for all ExoMars TGO science operations. The PS and ESWT, in coordination with the SOC will define the overall concept for science operations during the early phases of mission implementation.

ESA will capture science operations requirements and monitor their implementation through the Science Implementation Requirements Document (SIRD), to be responded to by the applicable Science (operation) Implementation Plans (SIPs) of the SOC and each instrument team, for their respective areas of responsibility.

The SOC is the only interface to the MOC during TGO routine operations and its functions include:

- Support the science operations planning by providing a centralised planning system.

- Prepare the long-term and short-term payload operations plan to be submitted to the MOC, based on PS and ESWT inputs.
- Provide “quick-look” tools to assess the quality of the instruments’ data—in coordination with instrument teams to optimise efficiency and avoid duplications of quick-look data accessibility and use.
- Set-up, maintain and run a pipeline ensuring the processing of raw instrument data (telemetry) until L1b level (un-calibrated science data), based on inputs (routine, calibration files and algorithms) provided by the instrument teams, where applicable.
- Distribute instrument raw data, L1b data products, and additional auxiliary data to the instrument teams;
- Provide Liaison Scientists (LS), where applicable;
- Define, develop, operate, and maintain the ExoMars TGO and EDM science data archive. Populate it with the data and mission products produced by the instrument teams for all mission phases (including spacecraft navigation data).
- Support the MOC in the preparation of the payload operations during the commissioning phase.

The SOC is responsible for the development, procurement, integration, validation and maintenance of all the software and hardware systems it must operate.

6.4 Rover Operations Control Centre

The Rover Operations Control Centre (ROCC) will be responsible for all ExoMars Rover science operations on the martian surface, which include the following functions:

- The optimisation of the ExoMars Rover science return through the definition and implementation of an efficient and cost effective science ground system.
- The definition and implementation of a rapid science data analysis capability, to be performed with the ESWT or an ESWT-designated team of investigators, to support the Rover and Pasteur payload science operations. It is expected that, at least during the nominal mission, the scientists will need to work in the ROCC. All necessary facilities, including conference rooms, projectors, screens, internet access, etc. must be made available at the ROCC.
- The definition of operations for all surface mission phases, including the planning and execution of the Rover egress manoeuvre from the landing platform.
- The planning and implementation of instrument operation timelines and command sequences as inputs to the Rover Operations Plan (ROP).
- The coordination and verification of all command sequences generated by the Rover instrument teams for the operation of the Rover and the instruments in the Pasteur payload before their submission to the MOC. In some cases this may require validating or testing using the Rover Engineering Model in a Mars Simulation Facility, which will be located within the ROCC.
- The creation, together with the ESWT and at regular intervals, of mission-highlights and main scientific results summaries.
- In coordination with ESAC, the preparation of guidelines for science data archiving, and the creation of the Pasteur Scientific Data Archive (PSDA), as part of the ESA Planetary Science Archive (PSA).
- In coordination with ESAC, making pre-processed data, including the Pasteur Scientific Data Archive available to the scientific community in accordance with ESA-approved procedures.

It is the responsibility of the ESWT and the Rover scientists, to provide timely inputs for the ROCC to support these tasks.

6.5 Data-Sharing Policy

The ownership, access, use and dissemination of raw and calibrated data resulting from all scientific instruments in the ExoMars missions shall be governed by Chapter III, Section II, Paragraphs 1 through 3, of the Rules on Information, Data and Intellectual Property, ESA/C/CLV/Rules 5 (Final), as adopted by the ESA Council Resolution on the Rules concerning Information, Data and Intellectual Property, ESA/C/CLV/Res. 4 (Final)[1]. The duration of the agreed prior access period, as mentioned in Par. 3(b) of the referenced document, shall be six months after reception and distribution of the data by the MOC. Thereafter, all data products will be made publicly accessible through the appropriate ESA and Roscosmos science archives.

6.5.1 Data Rights for TGO and EDM

For the TGO, the agreed six-month, prior-access privilege shall be granted to each instrument team and IDS. However, ESA and Roscosmos expect that science teams will work in a collaborative manner to maximise the mission‘s science return. Orbiter science results deemed necessary to prepare or to conduct ExoMars Rover and/or SP operations shall be made available immediately to the Rover and/or SP instrument teams and IDSs, as required.

For the EDM, the agreed six-month, prior-access privilege shall be granted to the DREAMS instrument team and to the AMELIA investigation team, within the scope of the selected investigations, and to any EDM IDS.

6.5.2 Data Rights for the Rover and Surface Platform

From the very beginning, in 2003, the Rover scientific community realised that the multidisciplinary nature of the search for signs of life on Mars requires that the instruments complement each other. This is necessary to identify suitable geological targets with good biomarker preservation potential, and for the recognition of life-related signatures and compounds. This convergence must be extended to the interpretation of the scientific results.

Investigators will only have a few hours to process and interpret instrument data to propose a sequence of Rover activities for the next sol. To achieve this rapid-reaction scientific response it is essential to develop a critical mass of knowledgeable scientists able to promptly analyse the mission’s results. Granting all selected scientists immediate and complete access to all Rover results is the only way to bring this about.

ESA will also ensure that the appropriate means are in place to provide a real-time flow of the main ExoMars scientific results to the public. This also requires a fast scientific response.

Summarising, ESA will grant all Rover instrument teams and IDSs immediate and complete access to the whole ExoMars Rover data set and to the utilisation of the data processing software, whether developed by the Agency or otherwise. ESA will ensure that appropriate and visible credit is given to all parties contributing instruments or data analysis tools in all publications, whether in the web or in peer-reviewed science journals. A plan to this effect will be proposed by the ESWT.

For the Rover, the agreed six-month, prior-access privilege shall be granted collectively to all selected scientists (instrument teams and IDSs).

Likewise, a sound characterisation of the environment based on the measurements the Surface Platform (SP) will conduct requires that the various data streams be combined and collectively interpreted.

Also for the SP, the agreed six-month, prior-access privilege shall be granted collectively to all SP selected scientists (instrument and IDS teams).

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[1] Council Resolution on the Rules concerning Information, Data and Intellectual Property, ESA/C(2002)3, 11 January 2002.

ESA and Roscosmos expect that the Rover and SP science teams will work in a collaborative manner to maximise the mission‘s science return.

6.5.3 Data Obligations

During the six-month prior access period, all PI teams will be required to share data with the ESWT members to enhance the programme’s return, in accordance with procedures to be agreed within the ESWT.

An exchange of quick-look data among the science teams, in graphic and/or image form, will take place as soon as possible, as per plans to be agreed between the PSs and the ESWT. This quick-look material will help improve the science interpretation of results, but shall be under strict embargo and cannot be used for scientific publications.

All scientific data products (the raw data sets, the relevant calibration data, the documentation, and any necessary software tools and information to use the data) shall be made available to the international scientific community not later than six months after reception and distribution of the data by the MOC. The PI teams will provide records of processed data with all relevant information on calibration and instrument properties to ESA and Roscosmos periodically, according to a delivery plan developed in agreement with the PSs. The ESA and Roscosmos science data archives will be the repository of all mission products.

The PI of each instrument team must ensure the timely delivery of all data products specified in the ExoMars Archiving Interface Control Document (AICD). The funding for these activities is considered to be part of an instrument cost at completion, and is therefore under the responsibility of each instrument team.

The teams shall endeavour to publish results in a timely manner, in appropriate scientific and technical journals. A publication policy will be established by the ESWT and implemented under coordination of the PSs (typically in what is called a “Rules of the Road” document). The services supplied by ESA, Roscosmos, and LFAs must be acknowledged in all publications.

The PI teams will have to provide ESA, Roscosmos (and where applicable, the LFA) with processed and useable data for science communication purposes as soon as possible after their receipt, even during their proprietary period.

In coordination with ESAC, the Rover Operations Control Centre (ROCC) will prepare and maintain the Pasteur Scientific Data Archive (PSDA) within six months of the receipt of data sets from the Rover instrument teams. The PSDA will become freely accessible online to all scientists through the ESA Planetary Science Archive (PSA) and through a mirror copy maintained at IKI (Russia).

Likewise, Roscosmos will archive and make available the ExoMars SP data. A copy of this data set will also be available in the ESA PSA.

Any commercial utilisation requests involving the use of information derived from the analysis of ExoMars data will be considered on a case-by-case basis, according to the rules laid down on Chapter III, Section III of the Rules on Information, Data and Intellectual Property, ESA/C/CLV/Rules 5 (Final).

6.6 Public Outreach and Science Communications

The ExoMars mission will attract much public interest. Therefore advance planning of Communications and Public Outreach (CPO) activities is essential. Each instrument team commits to produce, in real time, material for public relations and World Wide Web communications. ESA will ensure that all relevant LFAs are kept informed of CPO activities and that wherever appropriate CPO activities are coordinated with LFA press offices to ensure maximum impact

During the development phase, ESA supports a Web home page on the ExoMars missions as an information tool for the scientific community and the general public. After launch, a more elaborated home page will include the latest news on the mission, as well as preliminary scientific results and images, as soon as they become available.

The Agencies will have the responsibility for planning and carrying out all ExoMars CPO. The ExoMars mission will be included in the overall ESA Communications Plan (CP). A detailed ExoMars CP will be drafted in due time with inputs from the PSs. For the definition and detailed implementation of the CP, the Agencies will make use of professional and public communications experts who will be selected at an appropriate time. These experts will work under Agency supervision and in full coordination with the PM, PS, MM, and the ESWT.

For the purpose of public relation activities PIs will provide to ESA and Roscosmos unlimited access to all processed and analysed data, even during their proprietary period. This material shall not be used for scientific publication purposes.

The active cooperation of all ExoMars scientists and LFAs is essential for the success of the CPO activities. Hence, the PS will initiate and identify opportunities for publishing project-related reports and scientific results. CPO material suitable for release to the general public will be made available by the members of the ESWT upon their own initiative, or upon request from the PS, at any time during the development, operational, and post-operational phases of the mission.

All ExoMars scientists are required to inform the PS and the ESWT of any scientific publications they may have produced related to the mission (its scientific objectives, preparation of its instruments, field tests, calibration or modelling, scientific results, etc.). Pointers to the relevant papers will be included in the ExoMars web site.

7 LIST OF ACRONYMS AND ABBREVIATIONS

ABP	Aurora Board of Participants (2001–2005): Aurora's Programme Board, composed of delegates from all countries supporting the Aurora Programme. In 2006 it was merged with PB-HSR under a new programme board: PB-HME.
ALD	Analytical laboratory Drawer.
AO	Announcement of Opportunity.
Aurora	Aurora is ESA's optional programme for the human and robotic exploration of our Solar System.
CDF	Concurrent Design Facility: A tool utilised by ESA to perform mission feasibility studies. It is located in ESTEC, in the Netherlands.
Co-I	Co-investigator.
Co-PI	Co-Principal Investigator
CP	Communications Plan: The document detailing ESA communications and public relations activities to be undertaken in support of missions.
CPR	Communications and Public relations.
CI	Call for Ideas.
CM	Carrier Module. The spacecraft element transporting the DM to Mars.DM Descent Module. The part of the spacecraft composite that enters the atmosphere for landing—typically a capsule.
DTC	Deputy Team Coordinator (old nomenclature, currently Co-PI).
EDL	Entry, Descent, and Landing.
EDM	Entry, descent, and landing Demonstrator Module.
E-ICD	Experiment Interface Control Document.
E-IRD	Experiment Interface Requirements Document.
ELIPS	European Life and Physical Sciences in Space Programme: The science programme coordinating research in life and physical sciences, including exobiology, in the erstwhile Directorate of Human Spaceflight and Microgravity (HME), nowadays called Directorate of Human Spaceflight and Operations (HSO).
EMF	Exobiology Multi-User Facility: A forerunner of the Pasteur instrument payload.
EPAC	Exploration Programme Advisory Committee: The advisory body responsible for technical and scientific recommendations during the initial phase of the Aurora Programme. The Exploration Science and Technology Advisory Group (ESTAG) superseded EPAC in 2006. Since 2010 the Human Spaceflight and Exploration Science Advisory Committee (HESAC) fulfils this role.
ERA	Exobiology and Radiation Assembly: An exposure facility that flew during 1992–1993 on ESA's Eureca platform.
ESA	European Space Agency.
ESAC	European Space Astronomy Centre, in Madrid (ES).
ESOC	European Space Operations Centre, in Darmstadt (DE).

ESTAG Exploration Science and Technology Advisory Group (ESTAG). ESTAG was the advisory body responsible for technical and scientific recommendations to the Aurora Programme until 2006. Since 2010 the Human Spaceflight and Exploration Science Advisory Committee (HESAC) fulfils this role.

ESTEC European Space Technology and Research Centre: ESA's largest establishment, located in Noordwijk (NL).

ESWT ExoMars Science Working Team: The group of scientists that advises ESA on all aspects of the Programme affecting its scientific performance.

GCMS Gas Chromatograph / Mass Spectrometer: Two analytical instruments that, combined, are very useful to analyse complex gas mixtures. They can provide elemental, molecular, and isotopic abundances and composition.

GEP Geophysics & Environment Package, an instrument payload once studied for inclusion in the ExoMars mission's landing platform. This proved ultimately unviable.

GI Guest Investigator.

HESAC Human Spaceflight and Exploration Science Advisory Committee. Since 2010 HESAC is the senior advisory committee on matters regarding ESA's Aurora Exploration Programme.

IDS Interdisciplinary Scientist.

IKI Space Research Institute of the Russian Academy of Sciences.

IMA Instrument Multilateral Agreement: All the elements conducive to the timely and satisfactory completion of Instrument Projects are identified in an IMA, including the form and time of the commitments that Lead Funding Agencies (LFA) agree to make available to the Project.

IR Infrared.

IRev Implementation Review.

ISS International Space Station.

ITAR International Traffic in Arms Regulation.

LMC Life Marker Chip.

LoE Letter of Endorsement.

LPSAC Life and Physical Sciences Advisory Committee: The advisory body issuing scientific recommendations to the ELIPS Programme.

LSS Landing Site Selection.

LSSWG Landing Site Selection Working Group.

Mb Mega-bit: a unit of data volume equal to 2^{20} bits of information.

MER Mars Exploration Rovers: A NASA programme that landed two very successful rovers in 2004, devoted mainly to surface geochemistry and mineralogy research.

MEX Mars Express.

MM Mission Manager.

MOC Mission Operations Centre, to be located at ESOC, in Germany.

MOLA Mars Orbiter Laser Altimeter: An instrument for measuring relief height in NASA's Mars Global Surveyor (MGS). The 0-MOLA ellipse has become the *de facto* reference for measuring altitude on Mars.

MRO Mars Reconnaissance Orbiter.

MSL Mars Science laboratory: A NASA programme that landed the Curiosity rover on Gale crater in 2012.

NASA National Aeronautics and Space Administration—the space agency of the United States of America.

PB-HME Programme Board for the Human Spaceflight, Microgravity, and Exploration Programmes. From 2006 onwards it carries out the tasks previously undertaken by the ABP and PB-HSR.

PB-HSR The Programme Board for Human Spaceflight and Microgravity Research (until 2005). It grouped the delegates from all countries subscribing the ELIPS and ISS Programmes. In 2006 it was merged with the ABP under a new programme board: PB-HME.

PCR Payload Confirmation Review.

PI Principle Investigator.

PM Project Manager.

PS Project Scientist.

PSA Planetary Science Archive.

PSDA Pasteur Scientific Data Archive.

Pyr Pyrolysis is a technique to render organic compounds volatile by subjecting them to high temperatures. It is usually employed as a first stage in combination with a GCMS, resulting in a Pyr-GC-MS instrument. This method is sometimes also called Thermal Volatilisation (TV), and can be performed with or without involving derivatisation agents—chemical compounds that attach to small molecules to help render them volatile.

RHU Radioisotope Heating Units: Small radioactive devices used to warm up items in space payloads; particularly useful when electrical power is at a premium.

RISC Rover Instrument Steering Committee.

ROCC Rover Operations Control Centre, to be located at ALTEC, in Turin (ITA).

ROP Rover Operations Plan.

RTG Radioisotope Thermoelectric Generators: Radioactive units for generating electrical power. They are commonly used in deep space missions when solar power generation is not practical, i.e. for the Cassini-Huygens mission to Saturn. However, small RTGs can also be used to power surface landers.

SOC Science Operations Centre.

SP Surface Platform. The science element, part of the lander, that becomes active after Rover egress.

SPC Science Programme Committee: ESA's delegate body with decision authority on all matters in the mandatory Science Programme.

SPDS Sample Preparation and Distribution System.

SPOCC Surface Platform Science Operations Control Centre

SSAC	Space Science Advisory Committee. Senior advisory committee on matters regarding ESA's mandatory Science Programme.
SSEWG	Solar System and Exploration Working Group. The SSEWG provides scientific advice to the Science Programme and to the Exploration Programme in ESA.
SWT	Science Working Team: One of several groups of scientists advising on specific aspects of the ExoMars mission.
TC	Team Coordinator (old nomenclature, currently PI): The investigator representing all Team Members participating in an instrument science team. He/she is also responsible for the organisation and reporting of the instrument team's activities.
TGO	Trace Gas Orbiter.
TM	Team Member (old nomenclature, currently Co-I): Any of the investigators that are part of an instrument science team.
TT	Topical Team.
TRP	Technology Research Programme: A study programme managed by ESA's Directorate of Technical and Operational Support that seeks to develop new technologies necessary for upcoming space missions.
UV	Ultraviolet, usually used for ultraviolet radiation or ultraviolet light.
WG	Working Group: In this document, it refers to the Pasteur Working Groups of scientists that have contributed to define the model instrument payload.

A1 SCIENTIFIC DESCRIPTION

A1.1 The 2016 ExoMars Mission

The 2016 mission will pursue the following science objectives: It will study martian atmospheric trace gases and their sources, contributing to the search for signs of possible present life on Mars. The latter will be pursued through a careful analysis of the association among minor atmospheric constituents and isotope ratios. The TGO (see Fig. A1) will also investigate the planet's surface and subsurface. The EDM will land on Mars and conduct *in situ* environmental measurements.

A1.1.1 The ExoMars Trace Gas Orbiter

Fig. A1: Artist depiction of the ExoMars Trace Gas Orbiter (TGO). Credit: ESA/Ducros.

Table A1 presents the four TGO investigations. NOMAD groups two infrared (IR) and one ultraviolet (UV) channel, while ACS has three IR channels. Combined, these two instruments will provide the most extensive spectral coverage of martian atmospheric processes so far. To achieve the very high sensitivity required to allow NOMAD and ACS to detect species existing in very minute abundances, these instruments need to operate in "Solar Occultation" mode. Twice per orbit, at local sunrise and sunset, they are able observe the Sun as it shines through the atmospheric column. In essence, they use our star as a very bright IR lamp. The Sun is so luminous that the signal-to-noise ratio is very high. Detection of atmospheric trace species at parts-per-billion level will be possible. NOMAD and ACS can also operate in "Limb Scanning" mode and in "Nadir Pointing" mode. The instruments can look directly down at the planet. However, here they must observe IR light reflected of the surface as it shines through the atmosphere. In this case the signal is very weak. The strategy to achieve an acceptable signal-to-noise level is to reduce the noise. This requires cooling the detector and part of the optics, which is very challenging. On the other hand, this mode allows studying the atmosphere draped over the surface, and hopefully may help to identify sources and sinks for interesting species.

One gas species that has elicited much interest is methane (CH_4). On Earth it is methanogenic bacteria that produce most of our methane. Alternatively, it can be exhaled as the result of certain subsurface hydrothermal processes, such as serpentinisation. The PFS instrument on board Mars Express made a first possible detection of methane in the martian atmosphere. Contemporary observations from Earth, using IR spectrometers in association with ground telescopes, have provided similar information. Because the Mars Express result was close to the detection floor of the instrument, and since the ground observations were obtained looking at Mars through Earth's atmosphere, which itself has a sizeable methane component, the scientific community would like to see this methane signature verified. Recently, MSL/Curiosity searched for a methane signal with its SAM instrument, but did not find any. It could be that Curiosity is not in the right location, or season, or that the methane is not present on the ground, but higher up in the atmosphere. With NOMAD and ACS, the TGO will be able to conduct a planet-wide observation campaign across a full martian year. It will be possible to detect methane and many other hydrocarbon species. If the presence of methane is confirmed, its association with other gases, as well as a careful analysis of isotopic ratios, will help us to determine whether its origin is biological or geological, or perhaps a combination of both. In either case, this would indicate that Mars remains an active planet.

Two other instruments will observe the martian surface. CaSSIS is a high-resolution (approximately ≤5 m/pixel), colour, stereo camera. Its innovative design allows obtaining co-registered image pairs, such that every photograph is stereo. This is very important for building accurate Digital Elevation Models (DEM) of the martian surface. CaSSIS will be used to study interesting geological formations that may be associated with trace gas detections. It will also be an important tool for characterising candidate landing site locations for future missions. Finally, FREND is a neutron detector that can provide information on the presence of hydrogen, in the form of water or hydrated minerals, on the surface's top 1-m layer. A similar instrument flew on board NASA's 2001 Odyssey, providing a first map of global surface water distribution. FREND will be capable of improving significantly the ground coverage resolution of the existing subsurface water map.

Following the release of the EDM from the hyperbolic Mars-arrival trajectory, the TGO will first settle into an intermediate orbit. From there it will conduct an approximately 9-month long aerobraking campaign to achieve its science orbit: Approximately circular, with about 400-km altitude, and a 74° nominal inclination. The orbit's inclination has been selected to maximise the number of sun occultations during the mission, while providing a good seasonal and latitude coverage.

Instrument	Scientific Rationale
Trace Gases:	Provide a detailed characterisation of the martian atmospheric composition, including trace species at ppb level. Map the distribution of trace gases, identifying sources and sinks, and study geographical distribution and temporal variability. The two instrument suites will work in partnership to maximise the science results.
Suite of 2 Infrared (IR) and 1 Ultraviolet (UV) spectrometer	NOMAD: The two infrared channels cover the 2.2–4.3 μm band (to target trace gases and atmospheric escape), whereas the ultraviolet and visible channel spans the 0.20–0.65 μm range (to investigate aerosols and ozone).
Cluster of 3 IR Spectrometers	ACS: The three spectrometers cover respectively the bands 0.7–1.7 μm, 2.3–4.6 μm., and 1.7–17.0 μm. ACS will study trace gases, profile isotope ratios, and contribute to atmospheric escape studies.
Camera:	To perform photo geological investigations on zones deemed interesting as possible sources of important trace gases. To characterise candidate landing sites for future missions.
Stereo camera	CaSSIS: High-resolution camera (≤5 m/pixel), capable of producing co-registered colour, stereo image pairs.
Subsurface:	Obtain improved coverage of subsurface water and hydrated minerals in the top 1-m layer of the martian surface with the objective to achieve ten times better resolution than previous measurements.
Neutron Spectrometer	FREND: Neutron detector with a collimation module to significantly narrow the instrument's field of view, thus allowing the creation of higher resolution maps of hydrogen distribution.

Table A1: ExoMars TGO investigations.

A1.1.2 The ExoMars EDM

The EDM has been conceived as a technology demonstration platform (see Fig. A2). Its objective is to achieve Europe's first landing on Mars. The EDM will enter Mars' atmosphere from the hyperbolic arrival trajectory. It will use a heat shield to slow down sufficiently to deploy a supersonic parachute. The final stages of the landing will be performed using pulsed liquid engines. Approximately a metre above ground the EDM engines will turn off. The platform will land on a crushable structure, designed to deform and absorb the final touchdown impact. Throughout the descent, the AMELIA science team will perform investigations using various EDM sensors to recover a number of atmospheric parameters, including density. The EDM will land during the statistical dust storm season. No entry profiles have been obtained during this time of the year when Mars' atmosphere is dust loaded. This will be very important information for designing future landed missions. Finally, the EDM also includes a small environmental station, DREAMS, that will operate using the available energy provided by on-board batteries. DREAMS will measure a number of atmospheric parameters: Temperature, pressure, humidity, wind speed and direction, optical depth, and—for the first time—atmospheric electrical charging. The EDM will also include a descent camera. The EDM science is presented in Table A3.

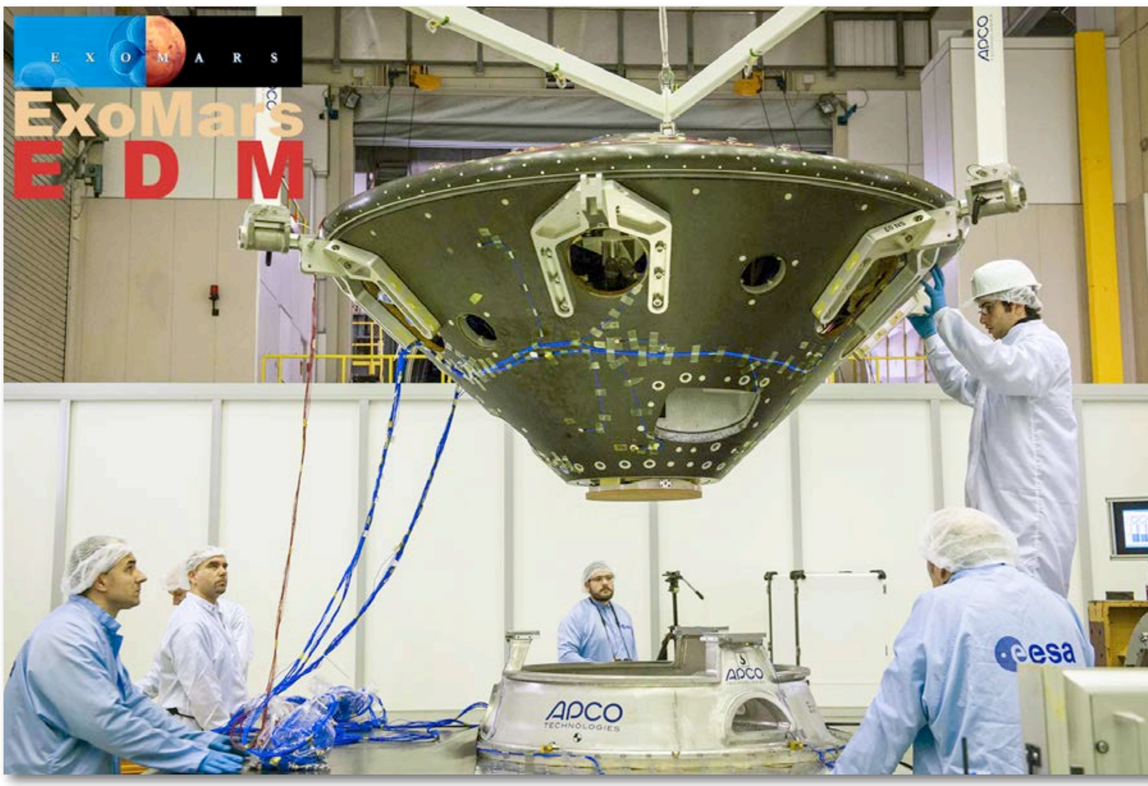

Fig. A2: Structural and Thermal Model (STM) of the EDM is being prepared to undergo vibration tests at ESTEC during March 2013.

Investigation	Scientific Rationale
Descent Science:	To study the martian atmosphere and obtain images throughout the EDM's descent.
Accelerometers, heat shield sensors	AMELIA: Utilise the EDM's engineering data to reconstruct its trajectory and determine atmospheric conditions, such as density and wind, from a high altitude to the surface. Use these results to improve atmospheric models.
Surface Science:	To characterise the surface environment in the presence of a dust-rich atmosphere.
Environmental Station	DREAMS: Conduct a series of short observations to establish temperature, pressure, humidity, wind speed and direction, optical opacity (dust loading), and atmospheric charging (electric fields) at the EDM's location.

Table A3: ExoMars EDM investigations.

A1.2 The 2018 ExoMars Mission

The 2018 mission will address the programme's two top science objectives and all of the technical objectives. The ExoMars Rover will carry a comprehensive suite of instruments dedicated to exobiology and geology research named after Louis Pasteur. The Rover will be able to travel several kilometres searching for traces of past and present signs of life. It will do this by collecting and analysing samples from within rocky outcrops, and from the subsurface—down to 2-m depth. The very powerful combination of mobility with the ability to access locations where organic molecules can be well preserved is unique to this mission. After the Rover will have egressed, the ExoMars Surface Platform (SP) will begin its science mission: To study the surface and subsurface environment at the landing location.

A1.2.1 The ExoMars Rover and the Search for Signs of Life

In attempting to define an effective strategy to search for carbon-based life on Mars, a useful approach is to initially consider separately the issues of past and present life detection; and subsequently, to look for a common way to address both cases.

A1.2.1.1 Extinct Life

If life ever arose on the red planet, it probably did when Mars was warmer and wetter, sometime within the first billion years following planetary formation. Conditions then were similar to those when microbes gained a foothold on the young Earth. Both planets were habitable in the sense of having the necessary environmental conditions and ingredients for life; namely, liquid water, carbon and other essential elements, as well as a source of energy. Life could have arisen in suitable locations, such as in the vicinity of hydrothermal activity, where all requirements and ingredients could have existed, also if most standing bodies of water were ice-covered. Not even intensive bombardment and possible volcanic resurfacing could have eradicated simple cells completely from the entire planet‘s surface. This marks Mars as a primary target for the search for signs of life in our solar system.

Unfortunately, on our planet, high-temperature metamorphic processes and plate tectonics have resulted in the alteration and/or destruction of most ancient terrains. It is very difficult to find rocks on Earth older than 3 billion years in good condition. Hence, the physico chemical record of the appearance and very early evolution of life on Earth is no longer accessible to us. The ensuing chemical and isotopic degradation of many putative bacterial fossils makes their reliable identification far from trivial. A further complication is that a range of inorganic processes is known to result in mineral structures closely resembling simple biological shapes. This issue lies at the heart of a heated debate among palaeobiologists. Two recent examples that have attracted much attention are the early Archaean⋆ rock specimens, obtained from the Pilbara region in Western Australia, claimed to contain Earth's oldest fossils to date; and the martian meteorite ALH84001, whose alleged fossil microorganisms were seen worldwide in 1996: These structures are most likely not biogenic. The difficulty is that, in essence, we are looking for rare remnants of microscopic, unshelled, uncompartmentalised beings whose fossilised forms can be confused with mineral precipitates. It is therefore doubtful that the living origin of ancient candidate microfossils may be accurately established on the basis of their morphology alone. Although important, comparative anatomy by itself cannot be relied upon to provide sufficient proof.

Another useful clue may lie in the isotopic signature of carbon. Many life processes favour the assimilation of the light isotope, ^{12}C, over that having an extra neutron, ^{13}C. This gives rise to a higher concentration of ^{12}C in living cells relative to the one found in the surrounding dead environment. For instance, the enzymatic uptake of carbon during methanogenesis can result in a $^{12}C/^{13}C$ ratio significantly higher than the one used as standard for terrestrial abiotic material. Consequently, provided they can be isolated, carbon residues stemming from previously living matter may be recognised by their ^{12}C enrichment. However, the heating of rocks to high temperatures, for instance during impact metamorphism, quickly converts any original cell material to graphite, changing this signal and making it hard to interpret. Furthermore, most organisms produce a range of overlapping isotopic signatures and, to complicate matters even more, an important abiotic process for organic synthesis in hydrothermal systems (Fischer-Tropsch) produces carbon compounds having

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⋆ *Archaean:* The earliest part of the Precambrian era on Earth, approximately 3.8–2.5 billion years ago.

✧ *Enantiomer:* From the Greek *enantios*, denoting "opposite" or "opposing."

❖ *Homochirality:* Compound word derived from Greek, meaning "same handedness."

isotopic signatures that overlap with biotic ones. For a useful interpretation of isotope biosignatures, a detailed understanding of the sources and sinks, as well as their temporal evolution, is crucial.

Some compounds synthesised by living organisms are relatively stable and can be preserved for a billion years or more after the parent cells have died and decomposed. It is not the whole molecule that survives, but rather the backbone of carbon atoms with its distinctive geometry. Typical examples are amino acids; the lipids that comprise cell walls; and some important pigments, such as bacteriochlorophyll and chlorophyll that absorb light to power photosynthesis in bacteria and plants. These telltale molecules are very common on our planet and can constitute very reliable biomarkers. Identifying one of them could prove as informative as finding a dinosaur bone.

Regrettably, a major problem with the study of biomarkers is that they degrade over time, and many decompose when exposed to temperatures greater than 200 °C. As already discussed, many, but not all, Archaean rocks on Earth have been heated beyond this value. Note, however, that organic molecules associated with life can exist in rocks more than 3 billion years old, although they are typically highly degraded. In such cases, it is the complexity of the molecular composition that helps to distinguish these molecules from abiotic organic molecules such as those found in meteorites. Thus, molecular complexity can provide an indication of biogenicity despite the potentially degraded nature of organic molecules. Mars, on the other hand, has not suffered such widespread tectonic activity. This would imply that rock formations from the earliest period of martian history, which have not been exposed to high-temperature recycling, are likely to exist. Consequently, well-preserved, ancient biomarkers may still be accessible for analysis.

Two of life's most important molecular building blocks —amino acids and sugars— can exist in left- and right-handed configurations called enantiomers✧ (Fig. A3) which, like a pair of gloves, are mirror images of one another. On Earth all living organisms use one enantiomer only: left-handed in the case of amino acids and right-handed for sugars. This property of homochirality❖ is essential for an efficient metabolism. Key life processes, such as protein synthesis and gene transcription, rely on amino acids and sugars having the correct spatial conformation to "shake hands" at molecular level with their counterparts. Conversely, synthetic chemicals prepared in the laboratory exhibit equal abundances of both right- and left-handed enantiomers —such a mixture is said to be racemic. Homochirality probably constitutes the most reliable indicator of the biological vs. abiotic origin of organic molecules. Surely, testing for homochirality becomes crucial when searching for life. However, as in the previous methods outlined, unfortunately also this one suffers when the sample is exposed to high temperatures or wet conditions for extended periods.

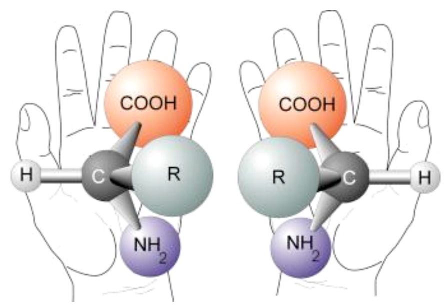

Fig. A3: Many of life's most important molecules can exist in left- or right-handed configurations. Credit: J. L. Bada, Scripps Inst. Ocean.

Summarising, the best chance to find signatures of ancient life on Mars is in the form of chemical biomarkers and fossil communities, either preserved underground or within surface rocks. A few life-detection methods —by no means exhaustive— were discussed to illustrate how important it is to use complementary techniques that, combined, give more credence to the proposition of a sample's biological potential. Several independent lines of evidence are required to construct a compelling case. ExoMars must therefore pursue a holistic search strategy, attacking the problem from multiple angles, including investigations to characterise potential habitats, visual examination of outcrops (morphology), and spectrochemical composition analyses performed on well-selected samples.

Liquid water being a prerequisite for active life, good candidate locations to look for biosignatures are terrains occupied by long-lasting bodies of water during Mars' early history. For example, within ancient lacustrine or marine sedimentary rocks that accumulated rapidly, where subsequent diagenesis✷ did not obliterate the original texture and compositional, isotopic, organic, and mineralogical evidence of the deposition envi-

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✧ *Enantiomer:* From the Greek *enantios*, denoting "opposite" or "opposing."

❖ *Homochirality:* Compound word derived from Greek, meaning "same handedness."

✷ *Diagenesis:* The physical and chemical changes occurring in sediments between the time of deposition and petrification.

ronment. The traces of ancient martian life, if it ever existed may be trapped within exposed, old sedimentary material and evaporitic deposits.

A1.2.1.2 Extant Life

In 1976, the twin Viking landers conducted the first *in situ* measurements focusing on the detection of organic compounds and life on Mars. The Viking biology package contained three experiments, all looking for signs of metabolism in soil samples. One of them, the Labelled-Release Experiment produced very provocative results. If other information had not been also available, these data could have been interpreted as proof of biological activity. However, theoretical modelling of the martian atmosphere and regolith chemistry hinted at the existence of powerful oxidants, which could more-or-less account for the results of the three biology package experiments. The biggest blow was the failure of the Viking Gas Chromatograph Mass Spectrometer (GCMS) to find evidence of organic molecules at the parts-per-billion level. With few exceptions, the majority of the scientific community concluded that the Viking results did not demonstrate the presence of extant life. Numerous attempts were made in the laboratory to simulate the reactions observed by the Viking biological package. While some reproduced certain aspects of the data, none succeeded entirely.

The next incremental step in our understanding of the martian surface was entirely unexpected. It came as a result of measurements conducted by the 2009 Phoenix lander in the northern subpolar plains. Phoenix included, for the first time, a wet chemistry analysis instrument that detected the presence of the perchlorate (ClO_4^-) anion in soil samples collected by the robotic arm. Perchlorates are interesting molecules. For example, ammonium perchlorate is regularly used as a powerful rocket fuel oxidiser. Its salts are chemically inert at room temperature, but when heated beyond a few hundred degrees, the four Oxygen atoms are released, becoming very reactive oxidation vectors. It did not take long for investigators to recall that Viking had relied on thermal volatilisation (in other words, heat) to release organics from soil samples. If perchlorate had been present in the soil at the two Viking lander locations, perhaps heating could explain the results obtained? A review of the Viking findings showed that some simple chlorinated organic molecules had been detected. At the time these compounds were interpreted to be rests of a cleaning agent used to prepare the spacecraft. More recently, the 2011 Mars Science Laboratory (MSL) has looked for organic molecules on samples drilled out of surface rocks. They have obtained the same chlorinated compounds as Viking. Hence, also the MSL results are consistent with the presence of perchlorate. We must therefore take these results into account for preparing ExoMars.

Undoubtedly, the present environment on Mars is exceedingly hostile for the widespread proliferation of surface life. It is too cold and dry, not to mention the large doses of UV radiation. Notwithstanding these hazards, basic organisms may still flourish in protected places: deep underground; at shallow depths, in especially benign environments; or within rock cracks and cavities.

Fig. A4: Example of a cryptoendolithic microorganism of the McMurdo Dry Valleys. These cold-adapted algae live in favourable microclimates, just beneath the surface of porous rocks facing the Sun. Credit: R. Kinne, NSF.

Perhaps a good step is to consider Earth ecosystems with conditions approximating those of the Red Planet. In this regard, it is the frigid desert of the Antarctic dry valleys (77° 45' S) that bears the closest resemblance to the martian environment today. This region has temperatures varying between –15 and 0°C in the summer, and as low as –60°C during the winter, with a relative humidity of 16 to 75%. The melting of the infrequent snow coverage on rocks is the main source of water for life there. The primary producers are photosynthetic endolithic microbial communities dominated by cryptoendolithic lichens. These microorganisms colonise a narrow zone a few millimetres beneath the surface of rocks (Fig. A4). This habitat provides a favourable microclimate, and is well protected from the harsh outside environment (strong winds, temperature fluctuations, desiccation, and UV radiation). Cryptoendolithic communities are only found in light coloured weathered or porous rocks because only these types of rocks offer the necessary substrate for colonisation of their interior, the permeability for the uptake of liquid water and moisture, and the translucent property required for the photosynthetic primary producer. Usually, endoliths grow only on the faces of rocks where the highest insolation is received: in Antarctica, north facing or horizontal. Water is provided to the rock by wind-blown snow or frost, which melts into the rock when it is warmed by sunlight. During the summer, freeze/thaw transitions are common (also contributing to the porosity of the rocks). The endoliths are wetted either by equilibration with the high humidity air in the rock, or by direct moisture uptake after snow/frost melt.

Life could have escaped the deteriorating climatic conditions on the surface of Mars by finding refuge in habitats that are very similar to those colonised by cryptoendolithic communities in Antarctica. Part of the investigations performed by the ExoMars Rover mission will be to determine whether this ever happened.

A1.2.1.3 The Martian Environment and the Need for Subsurface Exploration

For organisms to have emerged and evolved, liquid water must have been present on Mars. Without it, most cellular metabolic processes would not be possible. In the absence of water, life either ceases or slips into a quiescent mode. Hence, the search for extinct or extant life automatically translates into a search for liquid water-rich environments, past or present.

The strategy to find traces of past biological activity rests on the assumption that any surviving biosignatures of interest will be preserved in the geological record in the form of buried/encased remains, organic materials, and fossil communities. Similarly, because current martian surface conditions are hostile to most known organisms, also when looking for signs of extant life, the search methodology should focus on investigations in protected niches: in the subsurface and within surface outcrops. The same sampling device and instrumentation can adequately serve both types of studies. As will be explained in the next paragraphs, the rover's surface mobility and the 2-m vertical reach of the drill are both crucial for the scientific success of the mission.

The ExoMars rover will search for two types of life-related signatures: morphological and chemical. This will be complemented by an accurate determination of the geological context. Morphological information related to biological processes may be preserved on the surface of rocks. Possible examples include the microbially mediated deposition of sediments, fossilised microbial mats, stromatolitic mounds, etc. Such studies can only be accomplished with mobility and an imaging system capable of covering from the metre scale down to a sub-millimetre resolution (to discern micro-textural information in rocks).

Effective chemical identification of biosignatures requires access to well-preserved organic molecules. Because the martian atmosphere is more tenuous than Earth's, three important physical agents reach the surface of Mars with adverse effects for the long-term preservation of biomarkers: 1) The ultraviolet (UV) radiation dose is higher than on our planet and will quickly damage potential exposed organisms or biomolecules. 2) UV-induced photochemistry is responsible for the production of reactive oxidant species that, when activated, can also destroy biomarkers; the diffusion of oxidants into the subsurface is not well characterised and constitutes an important measurement that the mission must perform. Finally, 3) ionising radiation penetrates into the uppermost metres of the planet's subsurface. This causes a slow degradation process that, over many millions of years, can alter organic molecules beyond the detection sensitivity of analytical instruments. Please note that the ionising radiation effects are depth dependent: the material closer to the surface is exposed to a higher dose than that buried deeper.

The best opportunity for life to have gained a foothold on Mars was during the planet's very young history, when water was more abundant. It is therefore imperative that the rover be able to land on an ancient region including water-related deposits. However, the record of early martian life, if it ever existed, is likely to have escaped radiation and chemical damage only if trapped in the subsurface for long periods. Studies show that a subsurface penetration in the range of 2 m is necessary to recover well-preserved organics from the very early history of Mars. Additionally, it is essential to avoid loose dust deposits distributed by aeolian transport. While driven by the wind, this material has been processed by UV radiation, ionising radiation, and potential oxidants in the atmosphere and on the surface of Mars. Any organic biomarkers would be highly degraded in these samples. For all the above reasons, the ExoMars drill will be able to penetrate and obtain samples from well-consolidated (hard) formations, such as sedimentary rocks and evaporitic deposits, at various depths from 0 down to 2 m.

Fig. A5 presents an artist view of the Rover and drill on the surface of Mars. The Rover will monitor and control torque, thrust, penetration depth, and temperature of the drill bit. The drill's full 2-m extension is achieved by assembling four sections: one drill tool rod, with an internal shutter and sampling collection capability, plus three extension rods. The drill is also equipped with an IR spectrometer for mineralogy studies inside the borehole.

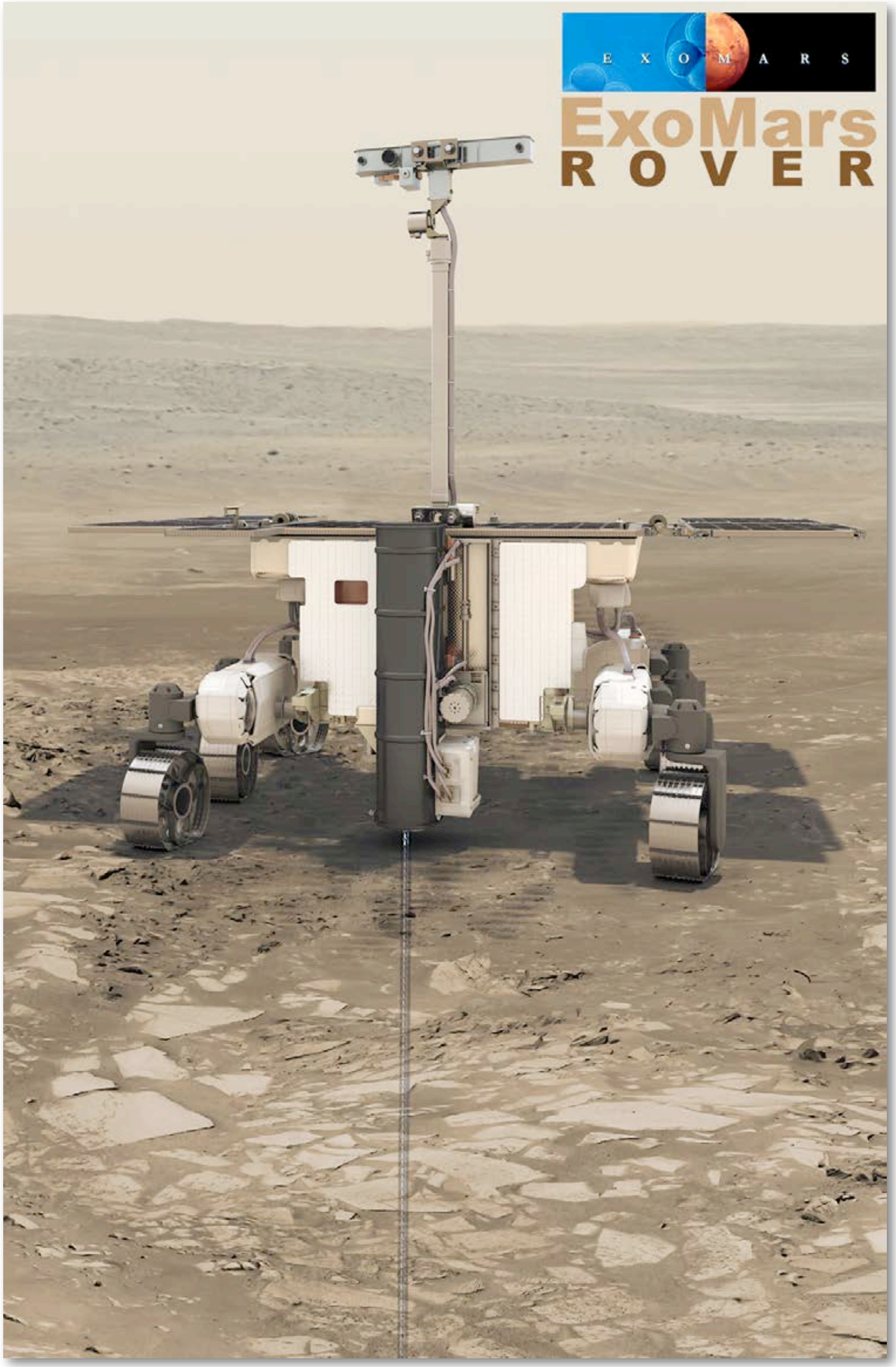

Fig. A5: ExoMars Rover showing the drill obtaining a sample from the martian subsurface.
Credit: ESA/Medialab.

A1.2.1.4 The Rover Science Mission

On Earth, microbial life quickly became a global phenomenon. If a similar explosive process occurred in the early history of Mars, then the chances of finding evidence of past life may be good. Even more interesting would be the discovery and study of life forms that have successfully adapted to modern Mars. However, this presupposes the prior identification of geologically suitable, life-friendly locations where it can be demonstrated that liquid water still exists—at least episodically throughout the year. None have been identified so far. For these reasons, the "Red Book[6]" science advisory team recommended (Table A4) that ESA focus mainly on the detection of extinct life; but also, build enough flexibility into the mission design to allow identifying present life.

The mission strategy to achieve the ExoMars rover's scientific objectives is: 1. To land on an ancient location possessing high exobiological interest for past (and/or present) life signatures, i.e. access to the appropriate geological environment. 2. To collect well preserved scientific samples (free from radiation damage and surface oxidation) at different sites, using a rover equipped with a drill capable of reaching well into the soil and surface rocks. This requires mobility and access to the subsurface. 3. At each site, to conduct an integral set of measurements at multiple scales to achieve a coherent understanding of the geological context and thus inform the search for biosignatures. Beginning with a panoramic assessment of the geological environment, the rover must progress to smaller-scale investigations of surface rock textures, and culminate with the collection of well-selected samples to be studied in its analytical laboratory. For the ExoMars rover to achieve high quality results regarding the possible existence of biosignatures, it must be delivered safely to a scientifically appropriate setting: ancient (older than 3.6 billion years, dating from Mars' early, more life friendly period), having abundant morphological and mineral evidence for long-term water activity, including numerous sedimentary outcrop targets distributed in the landing ellipse (to be sure the rover can get to some of them), and with little dust coverage.

Table A4: Mission strategy to achieve the ExoMars Rover's search-for-life objectives.

The ExoMars rover will have a nominal lifetime of 218 sols (approximately 6 months). During this period, it will ensure a regional mobility of several kilometres, relying on solar array electrical power.

The rover's Pasteur payload will produce self-consistent sets of measurements capable of providing reliable evidence, for or against, the existence of a range of biosignatures at each search location. As shown in Table A5, Pasteur contains: panoramic instruments (cameras, an infrared spectrometer, a ground-penetrating radar, and a neutron spectrometer); contact instruments for studying rocks and collected samples (a close-up imager and an infrared spectrometer in the drill head); a subsurface drill capable of reaching a depth of 2 m and obtaining specimens from bedrock; a Sample Preparation and Distribution System (SPDS); and the analytical laboratory, the latter including a visual + infrared imaging spectrometer, a Raman spectrometer, and a Laser-Desorption, Thermal-Volatilisation Gas Chromatograph Mass Spectrometer (LD + Der-TV GCMS).

If any organic compounds are detected on Mars, it will be important to show that they were not brought from Earth. Great care is being devoted during the assembly, testing, and integration of instruments and rover components. Strict organic cleanliness requirements apply to all parts that come into contact with the sample and to the rover assembly process. Once assembled, the analytical laboratory drawer will be sealed and kept at positive pressure, throughout transport, final integration, launch, cruise, and landing on Mars. The ExoMars rover will also carry a number of blank calibration samples to reliably demonstrate that it is free

[6] Exobiology in the Solar System and the Search for Life on Mars, "Red Book" Report from the ESA Exobiology Team Study, SP-1231, October 1999.

from contaminants. Upon landing, one of the first science actions will be for the drill to pass a blank sample to the analytical laboratory. After performing a full investigation, the results should indicate “no life” and “no organics.” Failure to obtain this first negative reading could invalidate any later search-for-life findings.

Instrument	Scientific Rationale
Panoramic Instruments:	To characterise the rover’s geological context, both on the surface and on the subsurface. Typical scales span from panoramic to 10 m, with a resolution in the order of 1 cm for close targets.
Panoramic Camera System	PanCam: Two wide-angle stereo cameras and 1 high-resolution camera; to investigate the rover’s environment and its geology. Also very important for target selection for more detailed, textural studies.
Infrared (IR) Spectrometer	ISEM: For bulk mineralogy characterisation, remote identification of water-related minerals, and for aiding PanCam with target selection.
Ground Penetrating Radar (GPR)	WISDOM: To establish subsurface stratigraphy down to 3-m depth, and to help plan the drilling strategy.
Neutron Spectrometer	ADRON: To determine the level of subsurface hydration, and the possible presence of ice.
Contact Instruments:	To investigate outcrops, surface rocks, and soils. Among the scientific interests at this scale are: macroscopic textures, structure, and layering. This information will be fundamental to understand the local depositional environment and to search for morphological biosignatures on rocks.
Close-Up Imager	CLUPI: To visually study rock targets at close range (50 cm) with sub-mm resolution. This instrument will also investigate the fines produced during drilling operations, and image samples collected by the drill. The close-up imager has variable focusing and can obtain high-resolution images at longer distances.
IR spectrometer in drill	Ma_MISS: For conducting mineralogical studies in the drill borehole’s walls.
Support Subsystems:	These essential devices are devoted to the acquisition and preparation of samples for detailed studies in the analytical laboratory. The mission’s ability to break new scientific ground, particularly for “signs of life” investigations, depends on these two subsystems.
Subsurface Drill	Capable of obtaining samples from 0 to 2-m depth, where organic molecules can be well preserved from radiation and oxidation damage. It also integrates temperature sensors and an infrared spectrometer.
Sample Preparation and Distribution System (SPDS)	Receives a sample from the drill system, prepares it for scientific analysis, and presents it to all analytical laboratory instruments. A very important function is to produce particulate material while preserving the organic and water content fractions.
Analytical Laboratory:	To conduct a detailed analysis of each collected sample. Following crushing of the sample, the initial step is a visual and spectroscopic investigation. Thereafter follows a first search for organic molecules. In case interesting results are found, the instruments are able to perform more detailed analyses.
VIS+IR Imaging Spectrometer	MicrOmega: Will examine the crushed sample material to characterise structure and composition at grain-size level. These measurements will also be used to help point the laser-based instruments, Raman and MOMA.
Raman Laser Spectrometer	RLS: To identify (at grain scale) the mineral phases present in the crushed sample material and determine their molecular composition (inorganic/organic).
Mars Organic Molecule Analyser	MOMA (LD + Der-TV GCMS): This is the rover’s largest instrument. Its goal is to conduct a broad-range, very-high sensitivity search for organic molecules in the collected sample. It incudes two different ways of extracting organics: 1) Laser Desorption (LD); and 2) Thermal Volatilisation (TV), with or without derivatisation (Der) agents, followed by separation using four Gas Chromatograph (GC) columns. The identification of the evolved organic molecules is performed with an ion trap Mass Spectrometer (MS).

Table A5: The Pasteur payload includes next-generation instruments: the first ground-penetrating radar, the first deep subsurface drill, the first drill spectrometer, the first IR imaging spectrometer, the first Raman spectrometer, and the first laser desorption organics analyser ever to be used on a planetary surface mission.

NASA’s very successful 2004 MER rovers were conceived as robotic geologists. They have demonstrated the past existence of wet environments on Mars. Phoenix 2009 provided important new results about the oxidation environment. But perhaps it is Mars Express 2003, together with MRO 2005, that have most advanced our understanding of past Mars, revealing multiple, ancient deposits containing clay minerals that can only have formed in the presence of liquid water. This reinforces the hypothesis that ancient Mars may have been wetter than it is today. MSL 2009 landed in Gale Crater to study the local geology and seek organics on the martian surface with the goal to identify habitable environments. It has established that conditions hospitable for life did indeed exist at Gale Crater. The ExoMars rover constitutes the next logical step.

ExoMars will have next-generation instruments to investigate whether life ever arose on the red planet. It will also be the first mission combining mobility with the capability to access locations where organic molecules can be well-preserved; thus allowing, for the first time, to investigate *in situ* Mars' third dimension: depth. This, by itself, is a guarantee that the mission will be able to break new scientific ground. The rover findings will be complemented by investigations performed on the Surface Platform.

With a longer-term perspective, understanding the scientific importance of subsurface material is fundamental prior to deciding which types of samples to return to Earth for further analyses. The ESA and Roscosmos ExoMars rover's findings constitute a key milestone for a future international Mars Sample return campaign.

A1.2.1.5 The ExoMars Surface Platform

The ExoMars Descent Module (DM) is the part of the spacecraft composite that enters the atmosphere to achieve a controlled descent and landing. The Carrier Module (CM) will take the DM to Mars and deliver it with a very precise entry angle. The DM will hit the top of the martian atmosphere at approximately 20,000 km/h. A thermal shield at the bottom of the capsule will be used to decelerate to roughly twice the speed of sound. Thereafter, the parachute system will take over. However, even after the main parachute has reached its terminal velocity, the DM will be still traveling at more than 300 km/h. The last stage will involve the use of throttled liquid engines. A multi-beam radar will measure the distance to ground and the horizontal speed over the terrain. The DM's computer will receive this information and combine it with its knowledge of the DM's attitude to decide how to exercise the engines and achieve a controlled landing. Legs will be used for the final touchdown (see Fig. A6).

Fig. A6: Artist view of the 2018 landing. The Rover is accommodated on top. The Surface Platform will begin its science mission once the Rover has descended to the surface. Credit: Lavochkin/ESA.

The Rover, which sits on top of the Surface Platform (SP), will then unfold its solar panels, camera mast, and wheels. The SP will deploy ramps that the rover can use to move onto the martian surface. Most likely, a few days will be required to image the surroundings and decide which is the safest exit direction for the rover to leave the lander. Once the Rover is on its way, the SP will conduct environment and geophysics experiments for about a martian year. A corresponding Announcement of Opportunity (AO) will be released.

A2 INSTRUMENTS AND INVESTIGATIONS

A2.1 ExoMars TGO Payload

IR and UV spectrometer suite (NOMAD):

NOMAD combines three spectrometers, two IR and one UV, to perform a high-sensitivity orbital identification of atmospheric components. NOMAD can work in Sun occultation mode, in nadir-pointing mode, and in limb scanning modes.

Principal Investigator (PI): Ann Carine Vandaele, Belgian Institute for Space Aeronomy, Brussels (B)
Co-PI: José Juan Lopez Moreno, Instituto de Astrofísica de Andalucía, Granada (E)
Co-PI: Manish Patel, The Open University, Milton Keynes (UK)
Co-PI: Giancarlo Bellucci, IAPS IFSI, Rome (I)

Atmospheric Chemistry Suite (ACS):

ACS is a suite of three IR spectrometers to investigate the chemistry, aerosols, and structure of the martian atmosphere. ACS can also work in Sun occultation, nadir-pointing, and limb-scanning modes.

Principal Investigator (PI): Oleg Korablev, Space Research Institute (IKI), Moscow (RUS)
Co-PI: Franck Montmessin, LATMOS, Paris (F)

Colour, Stereo Camera (CaSSIS):

A high-resolution (≤5 m/pixel), colour, stero camera to provide the geological and dynamical context for possible trace gas sources and sinks detected by NOMAD and ACS. CaSSIS will also be very useful for the characterisation of candidate landing sites.

Principal Investigator (PI): Nicolas Thomas, University of Bern (CH)
Co-PI: Gabriele Cremonese, OAPD INAF, Padova (I)

Neutron detector (FREND):

FREND is a high-resolution epithermal neutron detector that can be used to map the distribution of hydrogen (an hence infer the presence of water or hydrated minerals) in the top 1 m of the martian subsurface.

Principal Investigator (PI): Igor Mitrofanov, Space Research Institute (IKI), Moscow (RUS)

A2.2 ExoMars EDM Payload

Environment surface station (DREAMS):

DREAMS is a small package that to measure surface pressure, temperature, humidity, wind speed and direction, optical opacity (atmospheric dust content), and atmospheric charging;

Principal Investigator (PI): Francesca Esposito, INAF-Osservatorio Astronomico di Capodimonte, Naples (I)
Co-PI: Stefano Debei, CISAS, Università di Padova (I)
Lead Co-Is: MetWIND–Colin Wilson, Oxford University (UK); DREAMS-P and DREAMS-H–Ari-Matti Harri, Finnish Meteorological Institute, Helsinki (FIN); MarsTem–Giacomo Colombatti, CISAS, Università di Padova (I); SIS–Ignacio Arruego, INTA, Madrid (E); MicroARES–Franck Montmessin, LATMOS, Paris (F)

Entry and descent science investigations (AMELIA):

The team will study the EDM's engineering data to reconstruct its trajectory and determine important atmospheric parameters, such as density and wind from a high altitude to the surface. These measurements will be used to improve models of the martian atmosphere.

Principal Investigator (PI): Francesca Ferri, Università di Padova (I)
Co-PI–Modeling: François Forget, Laboratoire de Météorologie Dynamique, Paris (F)
Co-PI–Pressure and radio link science: Özgur Karatekin, Royal Observatory of Belgium, Brussels (B)
Co-PI–Assimilation: Stephen Lewis, The Open University, Milton Keynes (UK)

A2.3 ExoMars Rover Payload

Panoramic camera system (PanCam):

PanCam is designed to perform digital terrain mapping for the ExoMars rover mission. A powerful suite, consisting of a wide-angle, stereoscopic, colour camera pair, complemented by a high-resolution, colour camera, PanCam will allow characterising the geological environment at the sites the rover will visit —from panoramic (tens of metres) to millimetre scale. It will be used to study outcrops, rocks, and soils in detail, and to image samples collected by the drill before they are delivered to the analytical laboratory for analysis. PanCam can also be used for atmospheric studies.

Principal Investigator (PI): Andrew Coates, MSSL/University College London, London (UK)
Co-PI – High-Resolution Camera: Ralf Jaumann, DLR/IPF, Berlin, (D)
Co-PI – Wide-Angle Cameras: Jean-Luc Josset, Institute for Space Exploration, Neuchâtel (CH)

Infrared spectrometer (ISEM):
ISEM is a pencil-beam infrared spectrometer mounted on the Rover mast and co-registered with the Pancam high-resolution camera. ISEM will record IR spectra of solar light reflected of surface targets—such as rocks and soils— to determine their bulk mineralogical composition. ISEM will be a very useful tool to discriminate between various classes of minerals at a distance. This information can be employed to decide which target to approach for further studies. ISEM can also be used for atmospheric studies.

Principal Investigator (PI): Oleg Korablev, Space Research Institute (IKI), Moscow (RUS)

Shallow ground-penetrating radar (WISDOM):

The WISDOM radar will be very useful to characterise subsurface stratigraphy to a depth of 3–5 m with a resolution in the order of 2 cm. WISDOM will allow constructing three-dimensional subsurface maps and provide useful information to improve our understanding of the subsurface deposition environment on the sites the Rover will visit. Most importantly, WISDOM will identify layering and help select interesting buried formations from which to collect samples for analysis. Targets of particular interest for the ExoMars mission objectives are well-compacted, sedimentary deposits that could have been associated with past water-rich environments. This ability is likely fundamental to achieve the Rover's scientific objectives, as subsurface drilling is a resource-demanding operation that can require several sols.

Principal Investigator (PI): Valérie Ciarletti, LATMOS (F)
Co-PI: Svein-Eric Hamran, FFI, Oslo (N)
Co-PI: Dirk Plettemeier, TU-Dresden (D)

Subsurface neutron detector (ADRON):
ADRON will count the number of thermal and epithermal neutrons scattered in the martian subsurface to determine hydrogen content (present as grain adsorbed water, water ice, or in hydrated minerals) in the top 1 m. This information will complete the subsurface characterisation performed by WISDOM.

Principal Investigator (PI): Igor Mitrofanov, Space Research Institute (IKI), Moscow (RUS)

Close-Up Imager (CLUPI):

CLUPI will obtain much needed, high-resolution images (20-micron resolution) to study the depositional environment. By observing textures in detail, CLUPI will be able to characterise potential morphological biosignatures preserved on surface rocks. This is a function that exceeds the possibilities of PanCam. CLUPI will be accommodated on the drill box and have several viewing modes. CLUPI will be used to study rocks, soils, the fines produced during drilling, and also to image collected samples in high resolution prior to delivering them to the analytical laboratory.

Principal Investigator (PI): Jean-Luc Josset, Institute for Space Exploration, Neuchâtel (CH)
Co-PI: Frances Westall, Centre de Biophysique Moléculaire, CNRS, Orléans (F)
Co-PI: Beda Hofmann, Natural History Museum Bern (CH)

Ma_MISS:

Ma_MISS is a miniaturised IR spectrometer integrated in the drill tool. It will image the borehole wall created as the drill is operated. Ma_MISS will afford the unique capability to study subsurface stratigraphy and geochemistry *in situ*. This will be very important since samples may be altered following their extraction from their cold, subsurface conditions (–75 °C). The analysis of unexposed material by Ma_MISS, together with data obtained with the spectrometers located inside the rover, will be crucial for the unambiguous interpretation of the original conditions of martian rock formation.

Principal Investigator (PI): Maria Cristina De Sanctis, INAF, Rome (I)

MicrOmega:

After a collected sample is crushed in the analytical laboratory, MicrOmega will be the first instrument to be used to study the resulting material. MicrOmega will study mineral grain assemblages in detail to try to unravel their geological origin, structure, and composition. These data will be vital for interpreting past and present geological processes and environments on Mars. Because MicrOmega is an imaging instrument, it can also identify grains that are particularly interesting, and assign them as targets for Raman and MOMA-LDMS observations. This is a very useful property.

Principal Investigator (PI): Jean-Pierre Bibring, Institut d'Astrophysique Spatiale, Orsay (F)
Co-PI: Nicolas Thomas, University of Bern (CH)
Co-PI: Frances Westall, Centre de Biologie Moléculaire, CNRS, Orléans (F)

Raman Laser Spectrometer (RLS):

The Raman spectrometer provides geological and mineralogical context information for igneous, metamorphic, and sedimentary processes, especially water-related geo-processes (e.g. chemical weathering, chemical precipitation from brines, etc.). In addition, it also permits detecting a wide variety of organic functional groups. Thus, Raman can contribute to the tactical aspects of exploration by providing a quick assessment of organic content prior to the analysis with other instruments, like MOMA. Raman constitutes a high-priority instrument for establishing the geological context of samples, for assessing habitability, and for helping with the detection of bulk organics and certain key pigments.

Principal Investigator (PI): Fernando Rull, Universidad de Valladolid/CAB (E)
Co-PI: Sylvestre Maurice, Observatoire Midi-Pyrénées, Toulouse (F)

Mars Organic Molecule Analyser (MOMA):

MOMA is the largest instrument in the rover, and the one directly targeting biomarkers. MOMA is able to identify a broad range of organic molecules with high analytical specificity, even if present at very low concentrations, in samples obtained with the ExoMars drill. MOMA will answer questions about the possible origin, evolution and distribution of complex organics and life on Mars. These important studies will be carried out through two main activities: 1) the detection of organic molecules, and 2) the possibility to establish their biotic or abiotic source by identifying the distribution of molecules and their chirality.

MOMA has two basic operational modes: Laser Desorption Mass Spectrometry (LDMS), to study large macromolecules and inorganic minerals; and Gas-Chromatograph Mass-Spectrometry (GCMS), for the analysis of volatile organic molecules. In MOMA-LDMS, crushed drill sample material is deposited in a refillable container. A high-power, pulsed laser ionises the sample. The resulting ions are guided into the mass spectrometer and analysed. In MOMA-GCMS, sample powder is used to fill one of thirty single-use ovens. The oven is sealed and heated up stepwise to a high temperature—for some ovens, in the presence of a derivatisation agent. The resulting gases are separated by gas chromatography and delivered to the shared mass spectrometer for analysis. This process is useful for small organic molecules, such as amino acids.

The MOMA instrument implements a highly innovative combination for the robotic analysis of organic molecules, including the derivatisation of primary amines to elucidate their chirality. Furthermore, the MOMA-LDMS mode of operation does not seem to be affected by the presence of perchlorate oxidants in the sample—recently detected by Phoenix and MSL.

Principal Investigator (PI): Fred Goesmann, Max-Planck-Institut für Sonnensystemforschung, Lindau (D)
Co-PI – MS: Will Brinckerhoff, Goddard Space Flight Center, Greenbelt (USA)
Co-PI – GC: François Raulin, LISA, Universités Paris 12 & 7 (F)

A2.4 ExoMars Surface Platform Payload

The ExoMars SP payload is still to be selected.

A3 PROGRAMME BACKGROUND

A3.1 Search-for-Life Interest

The term Exobiology, in its broadest definition, denotes the study of the origin, evolution and distribution of life in the universe. It is well established that life arose very early on the young Earth. Fossil records show that life had already attained a large degree of biological sophistication 3.5 billion years ago. Since then, it has proven extremely adaptable, colonising the most disparate ecological niches, from the very cold to the very hot, and spanning a wide range of pressure and chemical conditions. For organisms to have emerged and evolved, water must have been readily available on our planet. Life as we know it relies, above all else, upon liquid water. Without it, the metabolic activities of living cells are not possible. In the absence of water, life either ceases or slips into quiescence.

Mars today is cold, desolate and dry. Its surface exposed to sterilising and degrading ionising and ultraviolet (UV) radiation, which contribute to the formation of reactive oxidants. Low ambient temperature and pressure preclude the existence of liquid water; except, perhaps, in localised environments, and then only episodically. Nevertheless, numerous features; such as large channels, dendritic valley networks, gullies, water-altered minerals, and sedimentary rock formations; suggest the past action of surface liquid water on Mars —and lots of it. The sizes of martian outflow channels imply immense discharges, exceeding any floods known on Earth.

Mars' observable geological record spans approximately 4.5 billion years. From the number of superposed craters, the oldest terrain is believed to be about 4 billion years old, and the youngest possibly less than 100 million years old. Most valley networks are ancient (4.0–3.5 billion years old), but as many as 25–35% may be more recent. Today, water on Mars is only stable as ice at the poles, as permafrost in widespread underground deposits, and in trace amounts in the atmosphere. From a biological perspective, past liquid water itself motivates the question of life on Mars. If Mars' surface was warmer and wetter for the first 500 million years of its history, perhaps life may have arisen independently there, at more or less the same time as it did on Earth.

An alternative pathway may have been the transport of organisms embedded in meteoroids, delivered between Earth and Mars. Yet another hypothesis is that life may have developed within a warm, wet subterranean environment. In fact, given the discovery of a flourishing biosphere a kilometre below Earth's surface, a similar vast microbial community may be active on Mars, having long ago retreated into that ecological niche, following the disappearance of a more benign surface environment. The possibility that life may have evolved on Mars during an earlier period, when water existed on its surface, and that organisms may still exist underground, marks the planet as a prime candidate to search for life beyond Earth.

A3.2 Exobiology Research in ESA

Exobiology activities in ESA started in the 1980's with the preparation of experiments for the Exobiology and Radiation Assembly (ERA). ERA flew in 1992, on board the European Retrievable Carrier (EURECA) mission, and was active for almost a year. It provided results on the exposure of invertebrates, microorganisms, and organic molecules to long-term space conditions, such as UV radiation, cosmic radiation, and vacuum.

Other experiments were conducted using Biopan, a facility externally attached to the Russian Foton retrievable satellite. Biopan's upper shell opened when in orbit to expose its samples to space. At the end of its ten-day mission, the lid closed. To withstand the extreme heat of re-entry, the entire Biopan structure was protected by an ablative heat shield; and upon landing, the specimens were be retrieved and examined. Five flights took place in 1992, 1994, 1997, 1999, and 2005. Microbes, seeds, and organic molecules were subjected to the harsh low-Earth orbit environment in different manners: i.e. with and without radiation protection, to vacuum, or in the presence of a simulated atmosphere. The response of the samples was determined. It was found that unprotected bacterial spores were completely or nearly totally inactivated by the UV radiation. Thin layers of clay, rock, or meteorite material were only successful in UV shielding when they were in direct contact with the spores. Thus, concerning a possible scenario for the interplanetary transfer of life, the Biopan data suggest that small rock ejecta of a few cm in diameter may provide sufficient protection for organisms to survive the space journey. However, micron-sized grains, as invoked in some panspermia theories, would most likely prove inadequate.

Meteorites may be natural vehicles for transporting resistant life forms across space. Hence, also on Foton, suitable meteorite analogues, the Stone experiments, were subjected to the searing environment of spacecraft re-entry. In 1999 the first three rock samples were fixed to the Foton capsule's heat shield and recovered for study upon landing. The goal was to investigate why among the known meteorites believed to have come from Mars none is of sedimentary origin. Can sedimentary rocks survive reentry? Are they altered beyond recognition by their passage through the Earth's atmosphere? Stone provided valuable results on the physical and chemical modifications undergone by sedimentary rocks during atmospheric infall. The 2005 mission contained four additional rock specimens, this time also including microorganisms. The goal of this work was to simulate a meteorite's atmospheric impact, and to observe to which degree the embedded bacteria and spores were affected.

From 2007 onwards, EXPOSE has been mounted on an external payload site of the International Space Station (ISS). Carefully controlled parameters, such as space vacuum and well-defined wavebands of solar UV and cosmic radiation act on the samples, which can be combined with chemical and or physically protective agents. This helped to elucidate whether, and to what extent, meteoritic material may offer enough protection for life to remain viable after a long permanence in space. It also allowed the study of long-term survivability and damage/repair mechanisms operating in microorganisms under space conditions. Finally, EXPOSE has improved our understanding of space chemistry in the Solar System in relation to the origin of life. Organic molecules of biological interest; such as amino acids, peptides, and nucleic acids; have been exposed to characterise variations in their stability and reactivity. Additionally, powders of clay, meteorite, and terrestrial rock have been used to model the mineral fraction present in meteoroid and interstellar dust to understand their effect as filters or as potential catalysts.

Other ESA initiatives that (will) contribute to our knowledge of important prebiotic chemical processes are Rosetta and Huygens. Rosetta will be the first mission to orbit and land on a comet. It will collect essential information to understand the formation and evolution of our Solar System. Rosetta will also help to determine whether comets could have contributed to the origin of life on Earth by seeding our planet with complex organic molecules through impacts. Light, volatile substances carried by comets may have also played a role in supplying Earth's oceans and atmosphere.

ESA's Huygens probe, travelling to Titan aboard NASA's Cassini spacecraft, successfully completed its mission in 2005. Many scientists consider that the present composition of Titan's atmosphere—mainly nitrogen and methane—may closely resemble that of early Earth, before life began on our planet. Throughout its 2.5-hour descent, Huygens made a detailed study of Titan's atmosphere, and characterised its surface in the proximity of the landing site. Ultraviolet light from the Sun breaks methane molecules apart to produce a thick layer of smog at mid altitudes. An organic rain of methane- and nitrogen-containing aerosols falls steadily onto the satellite's surface, creating an Earth-like terrain of extended river networks. The results of Huygens reveal the uniqueness of Titan in the Solar System as a planetary-scale laboratory for studying prebiotic chemistry.

Missions to other planets not always work out the way they are planned. The Russian Mars '96 mission consisted of an orbiter, two landers, and two penetrators to perform subsurface measurements. It was launched in November 1996, but fell back to Earth due to a failure in the rocket's upper stage. Europe had contributed many instruments to Mars '96. With no possibility of a Russian reflight, in 1997, within the Science Programme, work started on the design and development of the first ESA spacecraft to visit another planet: Mars Express. Mars Express, comprising an orbiter and the Beagle-2 lander, was launched in 2003 using a Soyuz rocket. Still in operation, the mission continues to address a wide variety of scientific objectives, concentrating mainly on surface geology and mineralogy; subsurface structure; and atmospheric circulation, composition and long-term evolution.

Mars Express payload has identified signatures of water in liquid, solid, and vapour form. In particular, the radar experiment MARSIS has obtained data to construct polar underground water distribution maps to depths of a few kilometres. Other Mars Express instruments continue to break scientific ground with important discoveries. Among these are the volcanic and glacial structures observed by the High-Resolution Stereo Camera (HRSC); the detection of trace amounts of methane in the martian atmosphere by the Planetary Fourier Spectrometer (PFS), which some scientists believe to have a biogenic origin; and the identification of ancient, water-altered minerals by OMEGA. Mars Express will also prove extremely valuable to identify geological regions with good biosignature preservation potential that could become candidate landing sites for ExoMars.

Regrettably, the Beagle-2 lander failed. It was to undertake a detailed chemical and morphological study of its landing site; and look for water in the soil, in rocks, and in the atmosphere. It would have sampled material from protected niches—subsurface and rock interiors—with a mole and a rock grinder/corer mounted on a small robotic arm. Beagle-2 was designed to investigate the existence of carbonate minerals and to determine the samples' isotopic fractionation. It could also search for trace atmospheric species.

A3.2.1 The ESA Exobiology Science Team Study

As a logical progression from its activities in low Earth orbit, in 1997 ESA created an Exobiology Science Team. Its objective was to conduct a state of the art survey of exobiology research, and to formulate recommendations for the future search for life in the Solar System. The full findings were published in 1999, in ESA SP-1231, the so-called "Red Book Report".

The main recommendation was that Mars should constitute ESA's primary goal, and that efforts should mainly be directed to the search for extinct life. The team identified three fundamental requirements:

1. That the <u>landing area possess high exobiological interest</u>. This has not been the case in past missions. Locations rich in sedimentary deposits and relatively free from wind-blown dust should be targeted.

2. That samples be collected at different sites, with a rover containing a drill to reach well into the soil and surface rocks; i.e. <u>mobility and subsurface access</u>.

3. That an <u>integral set of measurements</u> be performed on each sample and on the place it is obtained from.

The team suggested the following instruments for an exobiology package: a microscope for general examination of the samples at a resolution of 3 μm, plus a close-up camera with 50 μm resolution; an infrared or Raman spectrometer for identifying minerals and organic molecules; an alpha-proton-X-ray spectrometer (APXS) for establishing the samples' atomic composition; a Mössbauer spectrometer for studying iron mineral compositions and oxidation states; a Gas Chromatograph Mass Spectrometer (GC-MS) for organic, inorganic, and isotopic molecular determination and for chirality measurements; and an oxidants sensor.

During 1999–2000, two parallel Phase A studies were undertaken to examine the feasibility to accommodate the instrument package proposed by the Exobiology Science Team in a Surveyor-class lander. At the time, NASA had very ambitious plans for the exploration of Mars, with missions to be launched every two years. ESA saw a potential for scientific cooperation through the contribution of one or more payload elements to a future US mission. The outcome of these industrial studies was a preliminary design concept for what was called the Exobiology Multi-User Facility (EMF).

A3.2.2 The 1999 Exobiology Announcement of Opportunity

In view of a possible collaboration with NASA, in 1999 ESA issued an Announcement of Opportunity (AO) requesting proposals for exobiology experiments to be performed on Mars using the EMF. No specific flight opportunity was identified at the time. The Agency would provide the infrastructure needed for the various instruments: mechanical, control, power, thermal, and communications. It would also furnish a drill unit and a sample distribution and preparation system. The investigators were to propose the scientific instruments.

Sadly, the unfortunate demise of the Mars Polar Lander and Mars Climate Orbiter put the joint-mission scenario on hold. NASA undertook a critical review of its Mars exploration programme. This resulted in a revised sequence, with fewer and less frequent missions than previously envisioned. All landers after the twin 2003 MER rovers (dedicated to the study of surface mineralogy) were postponed to 2009 and beyond. In view of these events, the conditions for participating in a US endeavour, as defined in the 1999 Exobiology

AO, were no longer realistic. ESA therefore decided to take the initiative in creating its own mission to search for life on Mars.

A3.3 The Aurora and ELIPS Programmes

Exobiology activities in ESA received a boost at the Ministerial Conference in Edinburgh, in November 2001, when the European ministers approved funding for two new important programmes: Aurora and ELIPS. The Aurora Programme was created to formulate and implement a European long-term plan for the robotic and human exploration of the Solar System, particularly of those bodies holding promise for life. The European Life and Physical Sciences in Space (ELIPS) programme would complement Aurora by supporting exobiology and ISS research in low Earth orbit.

To prepare for the future human exploration of Mars, the Aurora Programme would need to first develop the necessary technologies by conducting a number of robotic missions. These missions, however, would also have to resolve important scientific questions connected to exobiology, planetary protection, and hazards to human missions to Mars. For the early exploration phase, ESA assessed a range of possible robotic missions in cooperation with scientists. This resulted in the selection of the first two missions in the Aurora Programme. They were:

- ExoMars: A Rover exobiology mission for performing *in situ* analysis in search for traces of past and present life on Mars, and to study the environment in preparation for future human missions.
- Mars Sample Return (MSR): This challenging mission would return to Earth a small capsule carrying samples from the martian surface. It requires a Mars Orbiter, accommodating the Earth return and reentry capsule, and a composite Descent Module/Mars Ascent Vehicle. The Mars Ascent Vehicle would deliver the sample canister to a low-altitude Mars orbit. The Orbiter would then capture the canister and return it to Earth. The MSR mission would be implemented as an international collaboration effort.

The approval of the Aurora and ELIPS programmes signalled a strong commitment by the member states to continue supporting exobiology research, and ensure the further consolidation of Europe's role as an important partner in planetary exploration.

A3.4 The 2003 Pasteur Call for Ideas

During 2002, at its Concurrent Design Facility, ESA carried out a study to define the foundations for the first Aurora mission: ExoMars. This work resulted in a preliminary mission architecture concept, and helped to estimate the level of resources that would be available to perform surface science on the Red Planet. With this information in hand, in early 2003, the Agency issued its Pasteur Call for Ideas. Scientists were invited to propose instruments for the Pasteur payload and investigations to be performed with the ExoMars Rover. In their proposals, they were also requested to describe how their instrument would complement or enhance the results provided by other instruments.

> The Call for Ideas document explains in detail the approach to be used for the definition of the ExoMars science: The peer review outcome of the 2003 Call for Ideas will identify the Pasteur instruments and their operational scenario. Thereafter, scientists from the selected proposing teams will be invited to form Working Groups to advise ESA on the final instrument composition of Pasteur and on its utilisation on Mars.

The scientific organisation of the 2003 Call for Ideas adopted the following approach: In proposals addressing Pasteur and ExoMars, all investigators were considered equal Team Members, collectively contributing to the scientific excellence of the proposal and the mission—that is, there were no Principal- and Co-Investigators. The proposals specified a Team Coordinator whose role was to represent the Team Members, to organise and report the team's activities, and to convey any information received from ESA to the other Team Members.

The Pasteur Call for Ideas was open to investigators from all countries. However, for logistical reasons, all proposals' Team Coordinator had to be based in one of the ESA member states. The proposals also had to designate a Deputy Team Coordinator, to assist the Team Coordinator and to represent the science team. The Deputy Team Coordinator had to be from a different country than the Team Coordinator.

Large research undertakings such as ExoMars require an appropriate critical mass, and benefit greatly from an international dimension. Therefore, the requirement was introduced to include institutions from, at least, three European countries in the proposals' science teams. Furthermore, investigators were also encouraged to form multidisciplinary teams (i.e. incorporating planetary physicists, geochemists, biochemists, palaeobiologists, specialists in Antarctic organisms, instrument engineers, etc.), where Team Member skills would complement each other, resulting in a more thorough treatment of a given problem.

The scientific community's response was extremely encouraging: nearly 600 investigators; from 260 universities, research institutions, and companies; expressed their interest to participate in ExoMars. In all, 50 proposals were received. The proposing teams consisted of international, multidisciplinary groups of investigators. Thirty countries were represented: a demonstration that interest in exobiology research is shared across national borders, and that scientists favour international collaboration.

A3.4.1 Scientific Peer Evaluation

During September 2003, all instrument proposals were reviewed for scientific merit by a panel of independent experts drawn from the international scientific community.

Significant effort was devoted to the careful screening and selection of the peer panel members. The Pasteur peers came from 8 different countries, and were world-renowned experts in areas such as: analytical chemistry, bioanalytical instrumentation, microbiology, palaebiology, extremophile research, environmental chemistry, biogeochemistry, aqueous geochemistry, sedimentary geology, martian soil chemistry, mineralogy, spectrochemistry, environmental hazards, trace-element analysis, etc. Additionally, some of them had actively participated in previous landed missions on Mars. Many Pasteur peers served in editorial boards of prestigious scientific journals, and all of them had published extensively. Their curricula vitae were carefully screened, as well as their publication record, to verify their suitability and to check their independence from all proposals submitted.

The outcome of this selection was as follows*: Out of 50 proposals received, 22 scored higher than the required 75 points. Of this, 11 were "Very Good," 8 were "Excellent," and 3 "Outstanding." To demonstrate the international dimension of the proposed projects, it has been calculated that, on average, the teams consist of 11 research institutions from 5 different countries.

Additionally, there were 3 other proposals that were not recommended to be included in the next payload-definition stage because they did not target instruments. Nevertheless, the panel considered that valuable aspects of these proposals required ESA's attention, and issued specific recommendations for them.

In conclusion, the result of this Call for Ideas was very positive. ESA received a significant number of original and innovative proposals for instruments and investigations. At least one, and in some cases two, proposals were identified for each major instrument category. This formed a solid basis for the further definition of the ExoMars Rover.

A3.4.2 First Pasteur Working Groups Meeting

Following the peer review, the 22 recommended teams were invited to appoint two scientists from each proposal to serve in the Pasteur Working Groups. The objective of the Pasteur Working Groups was to advise ESA on the instrument composition of the Rover payload and on its utilisation on Mars.

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*ESA's Life and Physical Sciences Advisory Committee (LPSAC) and the Exploration Programme Advisory Committee (EPAC) endorsed the evaluation process and the results of this Call for Ideas on March and December 2003, respectively.

In March 2004, 40 scientists from the Pasteur-selected teams (representing approximately 400 investigators) gathered at ESA/ESTEC for a full week. They were requested to assign priorities to the measurements needed to accurately identify signs of past or present life on Mars, and to characterise surface hazards to humans. Three Working Groups were formed; on Life Detection, Geological Context, and Environment Information. With the assistance of a small ESA team, they conducted an in-depth analysis of the mission's science possibilities and of its technical constraints—as estimated at the time. As a result of very positive discussions, the Working Groups were able to compile spreadsheets containing priority lists (essential, very important, desirable) for the scientific investigations to be performed by the Rover payload. These spreadsheets also identified a comprehensive list of instruments that could be used to collect the required data, and reported their technical specifications, with estimates for the resources necessary to accommodate and operate them on the Rover.

Furthermore, the science team also recommended a science exploration scenario for ExoMars: It called for mobility, access to the subsurface, and research at multiple scales: starting with a visual/spectroscopic assessment of the geological environment around the Rover, progressing to smaller scale investigations through the study of interesting surface rocks using a suite of contact instruments, and culminating with the collection of appropriate samples to be analysed by the instruments inside the Rover's laboratory, named after the famous French chemist and bacteriologist Louis Pasteur.

A3.4.3 ESA Pasteur Technical Board

In accordance with what was announced at the Pasteur Working Groups meeting, an ESA Technical Board (13–16 April 2004) was instituted to further assess the TRL level of the various candidate instruments, and to propose a way ahead for the technical development of the Pasteur payload. This board consisted of eight project/instrument engineers and scientists from the Exploration Programme, the Science, and the Technical Directorates of ESA. The Technical Board studied the material compiled during the Working Groups Meeting and the presentations submitted by the scientists. It also consulted the original proposals. Additionally, for instruments that had been the subject of ESA contracts, the study officers were requested to report on their development status. As a result of this review, the Technical Board assigned each candidate instrument a colour code according to the following classification:

Green: The instrument has an advanced level of readiness: an end-to-end laboratory prototype exists and has been field-tested in a relevant environment (e.g. Antarctica, Atacama desert, etc.), or with natural samples. Alternatively, the instrument derives strongly from previous space heritage (i.e. Beagle II, Rosetta, MER, etc.) or is flight proven. The instrument's technical requirements are known, and its integration and deployment needs are well defined. The instrument is considered ready to be taken up by industry for integration and for development of the flight model.

Yellow: The instrument has a relatively advanced level of readiness: an end-to-end laboratory prototype exists; however, it may not yet have fully achieved the desired final configuration/capabilities. The prototype has been the subject of extensive ground/laboratory testing, and/or the instrument has recognisable space heritage. Although the instrument's final technical requirements can be estimated with reasonable certainty, and its integration and deployment needs are well defined, the instrument is not yet considered ready for development of the flight model. Nevertheless, the instrument can be brought to the required readiness level in a short time (<1 year) with an immediate, though modest, investment.

Orange: Although prototypes of key components may exist, the instrument does not yet possess the required technical maturity. However, the instrument is regarded as essential or very important to achieve the mission's scientific objectives. The instrument's final technical requirements can be estimated with reasonable certainty, and its integration and deployment needs are well understood. It is considered that the instrument can be brought to the required readiness level in an acceptable time (< 1.5 years), albeit with an immediate, high financial commitment. Including this instrument in the payload introduces a certain development risk; however, this may be offset by the added science benefits, and is therefore deemed acceptable provided an aggressive instrument breadboarding effort is timely implemented.

Red: The instrument does not presently possess the required technical maturity: a suitable end-to-end prototype does not yet exist, and therefore the instrument's final technical requirements cannot be estimated with reasonable accuracy. Alternatively, the instrument's integration and deployment needs are ill defined, or it is anticipated that their implementation would result in severe technical difficulties/constraints on other Rover subsystems. The inclusion of this instrument in the payload is considered an unacceptable development risk for the project.

The outcome of this review was the elimination of the "red" instruments; whenever possible, in favour of more technically advanced instruments that could provide—or partially provide—the required scientific information. Some very important "orange" instruments were retained. However, it was noted that they would require immediate, fast-track prototype development and testing efforts.

The results of the first Pasteur Working Groups meeting, the Technical Board's instrument list and recommendations, and the proposed way ahead regarding further Pasteur developments, were presented to the Exploration Programme Advisory Committee (EPAC) on 13 May 2004. The EPAC endorsed the work performed, approved the Agency's proposed plan of action, and authorised the release of the Pasteur instrument list, first to the scientific community for comments, and then to the industrial teams in charge of the Rover-Pasteur Phase A work.

A3.5 ExoMars Phase A Studies

ESA transmitted the Pasteur instrument list to the science teams for discussions during May-June 2004. This resulted in the correction of minor inaccuracies in the instrument list. Shortly thereafter, the Agency produced a new version of the Rover-Pasteur Phase A System Requirements Document (SRD), reflecting the revised payload composition. In parallel, the science teams were requested to prepare Instrument Information Packages (IIPs) for each Pasteur candidate instrument. The intention was to facilitate the work of the industrial teams by providing them with up to date information on the instruments and their development. The new SRD and the IIPs were sent to industry on July 2004. The instrument mass of the Phase A model payload was estimated at 24 kg.

During the second half of 2004, two Rover-Pasteur Phase A studies were conducted in consultation with the scientists and ESA. Their goal was to propose well-integrated concepts for Pasteur and the Rover, capable of realising the ExoMars science objectives. These activities were concluded in February 2005. The resulting Rover models, having a mass of approximately 250 kg, are shown in Fig. A7. The next step was to propagate the Rover designs upwards, to the Descent Module and other mission elements, to arrive to well-consolidated mission proposals. Extensions to the Phase A Mission contracts addressed this harmonisation work.

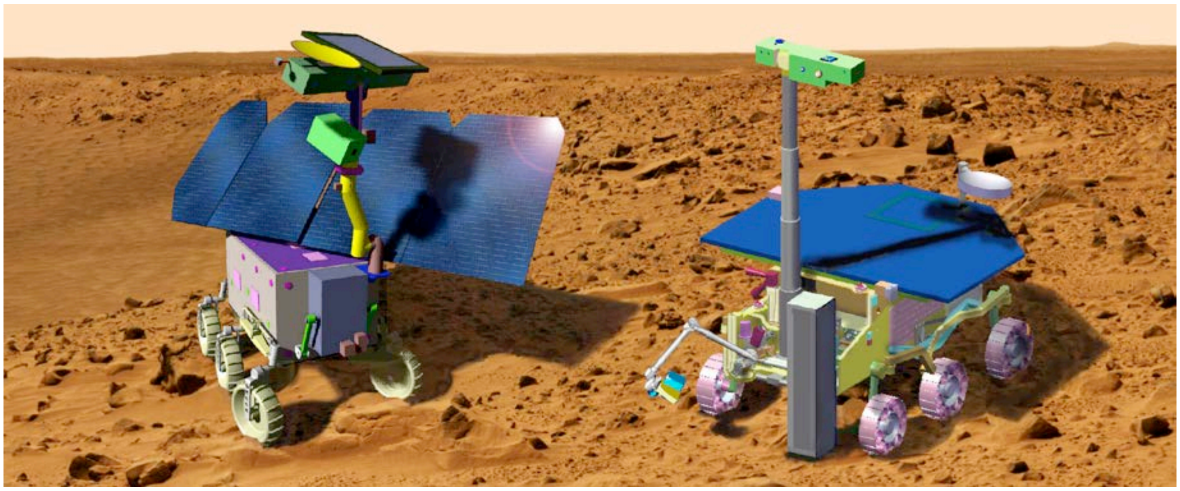

Fig. A7: Two possible Rover configurations were considered during the ExoMars Phase A. The first (left) relied on electric power to produce the heat necessary to survive on Mars; it therefore required a large solar array that must be pointed to the sun. Thermal conditioning in the second concept (right) was instead achieved using small Radioactive Heating Units (RHUs); this model included only a limited-size, horizontal solar panel.

A3.5.1 The Second Aurora Science Conference in Birmingham

On April 2005, European and international scientists met at the second international Aurora Science Conference, in Birmingham (UK). The goal of this gathering was to debate Mars robotic mission alternatives for 2011–2013. Three candidate missions were considered: ExoMars (Rover plus instrumented Orbiter), ExoMars (Rover only), and BeagleNet (a Beagle II derivative concept). Following scientific, technology, and programmatic presentations, an evaluation process of each mission was undertaken measured against well-identified criteria: 1) Scientific merit of the mission in relation to the Exploration Programme objectives; 2) Mission's relative scientific excellence versus cost; 3) Timeliness of the mission's science in the international context; and 4) Importance of the mission's technology for future planetary exploration activities.

The scientists favoured the Ariane 5 ExoMars version with rover and orbital science, but recognised that this option may not be affordable in the then European budgetary conditions. Following a long discussion, they agreed to recommend that the ExoMars Soyuz version, carrying the Rover and Pasteur, but no Orbiter, be implemented for a 2011 launch. The scientists stressed the importance of ExoMars to prepare Europe's participation in a future Mars Sample Return mission.

Following the recent cancellation of the NetLander mission, some participants requested ESA to include in ExoMars a provision for performing some geophysics and meteorology investigations—at the time estimated at 10 kg. This interest resulted in a proposal for the Geophysics & Environment Package (GEP).

A3.5.2 Second Pasteur Working Groups Meeting

During spring 2005, intense discussions at Programme Board (PB-HME) level, seeking to contain the overall mission cost in preparation for the 2005 ESA Ministerial Conference, resulted in a revised ExoMars mission concept: a Soyuz version, carrying the Rover and a small station, but no Orbiter. The mass allocation for the Rover and Pasteur was substantially reduced from that considered in the Phase A studies and a new element was introduced: the GEP.

To address the new concept's payload issues, 40 scientists from the Pasteur-selected teams gathered at ESA/ESTEC for the second Pasteur Working Groups meeting during September 2005. Also present were investigators from the GEP community and from ESA's advisory bodies, delegations, and NASA representatives. The participants recommended a payload of 12.5 kg for the Rover. They stressed that ExoMars, with its subsurface drill, would provide a unique opportunity to effectively search for life on Mars. Having reduced the Rover's instrument mass from 24 to 12.5 kg, they underlined that the recommended payload had to be considered the minimum necessary to do the job properly. The meeting concluded with a strong request by the scientists that the proposed 12.5-kg Pasteur payload for life detection be implemented in its entirety on board the Rover. Equally firmly was stressed the need to confirm the implementation of the previously identified Pasteur environment instruments on the ExoMars GEP station.

A3.5.3 2005 Ministerial Conference

The GEP was proposed as a small, 20-kg, autonomous package powered by Radioisotope Thermal Generators (RTG) to be provided as national contribution by France. However, by mid 2005 it became known that the RTG-based GEP configuration was not feasible. The project was then asked to study a solar powered version of GEP.

The ExoMars mission was approved at the ESA Ministerial Conference in Berlin, in December 2005.

A3.5.4 Payload Confirmation Review

The 2005 Declaration on the European Space Exploration Programme Aurora explicitly stated that the participating countries agreed to conduct an Implementation Review (IRev) of the ExoMars mission on the basis of:

- The results of the project's Systems Requirements Review (SRR);
- A committing industrial proposal for the development, launch, and operation of ExoMars; and
- The agreement of the participating states concerning the provision of the mission-selected instruments.

Upon concluding the Implementation Review, the participating states would confirm:

- The mission configuration (Baseline on Soyuz, Orbiter option on Ariane 5, or Baseline on Soyuz plus autonomous European data-relay communications orbiter, most likely on a second Soyuz).
- The final payload configuration; and
- The ExoMars launch date.

The decisions stemming from this review would determine the breadth of scientific objectives that ExoMars could pursue, as the choice of launcher and landing system had large implications for the Rover instrument mass and volume possibilities. The Ariane 5 configuration included a data relay Orbiter with its scientific payload.

The two main sources of information for IRev decisions would be the results of the Systems Requirements Review (SRR), and the recommendations of the Payload Confirmation Review (PCR). The SRR was an Agency level ESA review, which was implemented according to established rules and procedures. The SRR addressed all aspects of the mission to ensure that a coherent set of requirements existed that could allow Industry to prepare a committing technical, financial and programmatic proposal for the Baseline and optional mission configurations. This would provide two of the IRev inputs required by participating states. Another very important component of the Implementation Review regarded the scientific excellence of the ExoMars mission. This was addressed in the Payload Confirmation Review (PCR).

A3.5.5 Third Pasteur/GEP Working Groups Meeting

Forty scientists representing the Pasteur-selected teams and the GEP community gathered at ESTEC for the 3rd Pasteur/GEP Working Groups meeting on 20 October 2006.

ESA explained the need to timely define the ExoMars mission configuration and its final payload composition to meet the 2013 launch date. It presented the proposed PCR process and criteria, which were thoroughly discussed. The assembly recommended ESA and the member states to pursue the Ariane 5 mission, the one that could credibly and timely achieve the ExoMars scientific objectives.

A3.6 Phase B1 Activities

By end 2006, as the Phase B1 progressed, it became evident that a distributed GEP, powered by solar energy, entailed a mass in excess of 70 kg and could not be implemented. Efforts to remove the GEP from the mission were met with great resistance from Germany and France, who requested that ESA involve DLR and CNES in their studies and proceed with GEP. ESA had to consider in parallel three possible mission architectures.

A3.6.1 Payload Confirmation Review (PCR)

The 2007 Payload Confirmation Review (PCR) was organised to evaluate GEP candidate instruments and to reassess the Pasteur Rover instruments, subject to the constraints imposed by each of the mission architectures under consideration by the Project. Candidate instruments were rated for scientific merit. A technical assessment of the readiness level of the instruments was also performed.

The PCR was organised in two subsequent steps: first, a peer review, following the same rigorous, independent procedure utilised for the 2003 Pasteur Call; and secondly, an ESA/Industry technical review. A new candidate instrument for the Rover, MicrOmega, was also presented and reviewed. The outcomes of this exercise were 16.5-kg and 12.5-kg candidate payloads for the Rover and a small, 3.5-kg payload for the GEP. However, delegations were not satisfied with the 12.5-kg Rover payload, or with the fact that the GEP could not be included in a Soyuz-based mission. The executive indicated that a larger Rover payload and the GEP could be possible if an Ariane 5 launcher was used instead. The Programme Board (PB-HME) instructed ESA to pursue this avenue, and to seek the additional funding at the 2008 ESA Ministerial Conference.

A3.6.2 Fourth Pasteur/GEP Working Groups Meeting

Sixty investigators from the Pasteur and GEP communities met at ESTEC on 7–9 June 2007 for the 4th Pasteur/GEP Working Groups meeting.

ESA introduced the mission strategy that had been agreed with the Programme Board (PB-HME) to be presented at the 2008 Ministerial Conference. The new baseline would consist of a 2013 launch, using an Ariane 5 or a Proton launcher, and would include a Carrier and a large Descent Module (DM), but no Orbiter. Following a direct (T2), 9-month trajectory, the Carrier would go into a 4-sol orbit. The release of the DM would be "from orbit." The mission would deploy a 205-kg Rover and a 30-kg GEP on the surface of Mars. The new mission would be called Enhanced ExoMars. Its cost would be expected to exceed the amount allocated at the 2005 ESA Ministerial Conference.

At this meeting was also first proposed to name the GEP Humboldt, after the famous German explorer.

Following the PCR, it was also agreed to form the ExoMars Science Working Team (ESWT). The next science gathering would therefore be called the 1st ESWT meeting.

A3.6.3 First ExoMars Science Working Team Meeting

On 7–9 April 2008, 50 scientists (representing approximately 500 investigators) from the Pasteur, Humboldt, and Descent Science teams travelled to ESTEC for the first ExoMars Science Working Team (ESWT) meeting. Also present were observers from a number of instrument Lead Funding Agencies (LFA), including NASA.

During the first day, ESA and Industry described the state of advancement of the ExoMars project, stressing their commitment to launch in 2013. Detailed presentations covered the ExoMars mission configuration, the progress achieved in the definition of the rover and lander designs, and instrument visits planned to prepare for the Preliminary Design Review (PDR). The project team also answered questions posed by the scientific community.

On the second day were addressed the role of the ESWT and tasks requiring its support over the coming months. Also discussed were the rover and lander science exploration scenarios used to drive the mission's technical design in terms of available resources (data volume for transmission to ground, required energy, etc.). The science teams were presented with the latest spreadsheets and asked to provide feedback to ensure that the scenarios were consistent with mission and instruments' requirements and capabilities. During the afternoon, the Pasteur teams gave 15-min presentations on their instruments' objectives and implementation status. The work continued well into the night, with detailed updates to the Scientific Payload Requirements (SPR) document.

The morning of the third day was devoted to presentations by the Descent Science and Humboldt teams. Also discussed were the proposed landing site selection process for ExoMars and aspects of the reference surface missions for Rover and GEP.

A3.7 Phase B2 Activities

The mission made good technical progress during 2008. Despite this, the mass of the GEP implementation still proved prohibitive.

A3.7.1 2008 Ministerial Conference

The 2008 ESA Ministerial Conference was held in The Hague during November. The level of funding indicated by member states for ExoMars fell short of what was needed. The financial problem, coupled with a mass crisis due to the GEP and to a mass increase in the Rover candidate instruments, caused a launch delay to 2016 and meant that a reassessment of the mission architecture, scientific priorities, and instrument complement was necessary. This resulted in the 2009 Payload Confirmation Review #2 (PCR2).

While supportive of the ExoMars mission and its objectives, ministers instructed ESA to pursue international collaboration outside Europe as a means to reduce the implementation costs of ExoMars.

A3.7.2 Payload Confirmation Review #2 (PCR2)

The 2009 PCR2 panel identified five possible payload configurations addressing the Rover mission's scientific objectives, spanning the mass range 16.7 to 12.3 kg (called Options A–E respectively), with correspondingly decreasing science capabilities. The panel also underlined the need to preserve the 2.0-m depth reach in the drill, for scientific and reliability reasons. Finally, the panel recommended removing the GEP from ExoMars and flying its Humboldt instruments on an upcoming mission. This proved indeed the case, as these experiments constitute most of the payload on board NASA's InSight mission.

On the basis of the Rover mass the 2016 mission configuration could accommodate, the ExoMars Project proposed to implement Option D. Option D included seven instruments (PanCam, WISDOM, Ma_MISS, MicrOmega, Raman, MOMA, and MARS-XRD). The Programme Board (PB-HME) accepted this, but recommended that the project explore possibilities to reinforce the exobiology content of the Rover mission.

A3.7.3 Second ExoMars Science Working Team Meeting

On 1–2 July 2009, 50 scientists from the Pasteur and Humboldt science teams gathered at ESTEC for the second ExoMars Science Working Team (ESWT#2) meeting. Also present were instrument managers from a number of Lead Funding Agencies (LFA), including NASA, and ExoMars engineers from Industry.

ESA described the outcome of bilateral discussions in Plymouth with NASA aiming at implementing a cooperative programme for the robotic exploration of Mars. The scenario reported would result in an orbiter mission dedicated to data relay and the study of atmospheric trace gases in 2016, and postpone the launch of the ExoMars rover until 2018. This news dominated the discussions for the rest of the meeting, and was considered by the participants a worrying development. The ESWT considered that ExoMars should be developed as a European mission.

ESA also presented the state of advancement of the ExoMars Rover design and discussed a new Rover Reference Surface Mission—with the reformed Pasteur payload—for the case of one communications pass per sol.

Finally, the Pasteur teams gave 15-min talks on their instruments' status and science preparation, highlighting useful areas where the participation of investigators from other teams could be of help.

A3.8 The ESA-NASA Cooperation

During early 2009, technical studies at ESTEC and JPL had confirmed that it would not be possible to realise both agencies' Mars objectives on a large, single mission. Two missions would be necessary.

On November 2009, ESA and NASA signed a Letter of Agreement to develop a Mars Exploration Joint Initiative (MEJI), conceived as a collaborative framework programme. A first 2016 mission would include a Trace Gas Orbiter (requested by NASA) and an EDL Demonstrator (required by ESA). A second, 2018 mission would use a copy of the Mars Science Laboratory (MSL) skycrane to land two rovers perched atop a platform to be deposited on the martian surface. One would be the ExoMars rover, the other would be MAX-C, a rover to conduct surface studies, collect, and cache samples for future retrieval and return to Earth. The proposed programme configuration is shown in Fig. A8.

The original ExoMars objectives would be pursued with the 2016 EDL Demonstrator (for landing) and with the 2018 Rover (for exobiology). The TGO opened a new science possibility, and thus ExoMars acquired a third scientific objective, to study atmospheric trace gases and their sources, fitting the overall Programme's search for life theme. The payloads for the TGO, the EDM, and the NASA Rover would be competitively selected through dedicated, joint ESA-NASA AOs.

By January 2010 a joint NASA-ESA management structure had been put in place for guiding mission development activities. It included a Joint Mars Executive Board (JMEB), a Joint Mars Architecture Review Team (JMART), a Joint Science Working Group (JSWG), and a number of Joint Engineering Working Groups (JEWG). ESA, NASA, and JPL began to work on the Programme's technical and scientific implementation.

A3.8.1 Third ExoMars Science Working Team Meeting

On 3–4 February 2010, 40 scientists (representing approximately 400 investigators) from the Pasteur science teams gathered at ESTEC for the third ExoMars Science Working Team (ESWT#3) meeting. Also present were instrument managers from a number of LFAs and ExoMars engineers from the project team and industry.

In essence, during the ESWT#3, ESA presented the new Programme configuration. The two-rover concept was well received by the participants. They made a recommendation for studying the possibility to include ExoMars subsurface samples in the MAX-C rover cache.

Fig. A8: Initial ESA-NASA programme configuration. (Top) 2016 mission showing the TGO as it releases the EDM. (Bottom) The 2018 mission accommodating two rovers, side by side, on a platform, to be deposited on the martian surface using a copy of the MSL Skycrane system. One would be the ExoMars Rover, the other MAX-C.

A3.8.2 TGO and EDM Announcements of Opportunity

ESA and NASA released an AO for TGO instruments on 15 January 2010. During May and June 2010 the two agencies conducted a joint evaluation and coordinated selection process, leading to a mutually agreed payload. The TGO instrument complement would include one European (NOMAD) and four US instruments (MATMOS, EMCS, MAGIE, and HiSCI). MATMOS was a sun-occultation trace gas identifier with parts-per-trillion sensitivity. NOMAD would work in sun occultation mode, albeit with lower sensitivity, but would also have nadir and limb observing modes, allowing it to perform mapping of trace gases over the martian surface. EMCS would provide basic atmospheric state parameters, such as pressure, temperature, dust, and ice aerosol content. MAGIE was a wide-angle camera to observe cloud circulation patterns. Finally, HiSCI would obtain high-resolution, colour, stereo image pairs. The TGO selected payload would constitute a very powerful set of tools for studying atmospheric trace components.

The next mission element requiring urgent attention was the EDM. Conceived as a technology demonstrator, the EDM could nevertheless include a small scientific package. ESA and NASA issued an AO for EDM investigations on 30 November 2010. During March and April 2011 they conducted a joint evaluation process. The DREAMS surface payload and the AMELIA entry and descent science investigation were approved through a joint selection process.

A3.8.3 First Technical and Programmatic Challenges

While the activities on the 2016 mission were proceeding relatively well, things were not so good for the 2018 mission. Already by end 2010 it had become clear that landing two rovers on Mars using the Skycrane was technically unfeasible. The JMEB decided to abandon the two-rover concept and proposed to concentrate instead on one, much larger, MSL-class rover capable to perform the ExoMars and MAX-C science objectives. Integrating the ExoMars subsurface drill, ALD, and Pasteur payload, plus the MAX-C instrumented robotic arm and sample-caching system into a single platform was going to be a formidable challenge. ESA and NASA studied this new rover through most of 2011 (see Fig. A9). In the end the mass proved excessive, the volume too large, and the surface operations could not be accomplished within the expected 1 martian year nominal lifetime. Clearly some compromises would be required.

In the end, there was no need for painful rover choices. The reason was that grave programmatic problems rapidly overwhelmed any previously existing technical or scientific difficulties. In August 2011 NASA informed ESA that, due to budget reductions, they would no longer contribute the rocket launcher for the 2016 mission.

NASA and ESA decided to study programme alternatives aimed at reducing implementation costs. On 4 October 2011 the heads of ESA and Roscosmos met in South Africa and agreed to investigate the conditions for cooperating in the joint programme. Shortly thereafter, ESA and NASA agreed to proceed with the baseline programme, extending the international collaboration to Roscosmos. ESA presented this three-party way forward to its Council on 13 October 2011. Roscosmos would provide the 2016 launcher and fly some instruments on the TGO.

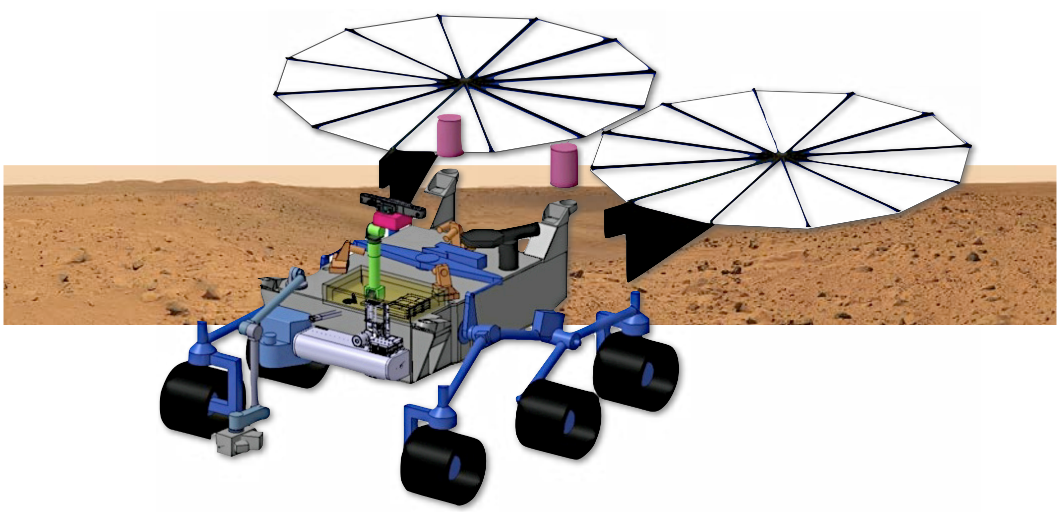

Fig. A9: Preliminary view of the joint 2018 rover in its solar power option. On the front left can be seen the instrumented robotic arm that would identify and collect samples for the cache—also visible in the front, left corner. The subsurface drill is shown in its horizontal, stowed position. It would collect surface and subsurface samples to be passed on to the Analytical Laboratory Drawer (ALD), depicted as a brown box immediately behind the drill. The mast, in green, would accommodate the ExoMars cameras and a spectrometer. A scientific disadvantage of this design was that its inability to cache subsurface samples collected with the drill. The project teams worked very hard to find a technical solution, but the marriage of these two complex systems would be impossible within the tight available constraints.

A3.8.4 Fourth ExoMars Science Working Team Meeting

On 13–14 October 2011, 30 scientists —representing approximately 400 investigators from the 2018 rover's Pasteur science community and 30 from the 2016 Entry, Descent, and Landing Demonstrator Module (EDM) science teams— gathered at ESTEC for the fourth ExoMars Science Working Team[7] (ESWT#4) meeting. Also present were instrument managers from a number of Lead Funding Agencies (LFA) and ExoMars engineers from the project team and industry.

The ESWT was informed of the latest programmatic developments. The ESWT#4 participants noted with concern that the utility of the Pasteur instruments in support of the joint rover's sample selection and caching activities had not been sufficiently recognised. They remarked that since the joint rover had a mass problem, having an AO for robotic arm and mast instruments seeking to duplicate the Pasteur instrument capabilities would not help. The resulting arm would likely be too large and heavy. Instead they proposed considering only essential instruments on a slimmer robotic arm, and studying a reference surface mission scenario in which the interest of specific samples for caching would be established using the Pasteur instruments. This would imply an arm design able to pass samples acquired with its corer to the Analytical Laboratory Drawer (ALD) for detailed analysis. The participants also remarked that the Pasteur external instruments (PanCam, CLUPI, WISDOM, and Ma_MISS) would also contribute important geological context information to the cache sample selection and acquisition process. The teams also proposed that ESA discuss with NASA and Roscosmos the possibility to implement, as soon as possible, a call for US and Russian participating scientists for the Pasteur payload instruments.

NASA and JPL did not quite agree with this suggestion, and considered a well-instrumented robotic arm a critical capability of the joint rover, necessary to quickly interrogate numerous surface targets.

A3.8.5 Demise of the ESA-NASA Joint Programme

A first meeting coming together of ESA, NASA, and Roscosmos, at ESA Headquarters, in Paris, on 7–8 December 2011, produced positive results. Roscosmos had previously provided technical data to ESA and NASA on a number of candidate instruments for possible accommodation on the TGO. During this meeting the three parties discussed which TGO experiments they would want to include. Based on the partners' priorities, considering the mission's scientific objectives, and on technical feasibility arguments, they identified following six instruments: MATMOS, NOMAD, and ACS for the upper deck; and HiSCI, EMCS, and FREND for the lower one. Also in this occasion, Roscosmos confirmed their intention to become a full programme member and contribute a Proton rocket for the 2016 mission.

The Agencies agreed on a calendar of frequent teleconferences and meetings for 2012, necessary to rapidly advance with the Programme's technical implementation. Unfortunately, soon thereafter, in January 2012, NASA announced that due to cuts to their proposed 2013 budget, they would no longer be in a position to participate as a major programme partner. Following a rapid reassessment of the situation, ESA and Roscosmos confirmed their interest in studying a joint implementation of the ExoMars Programme.

A3.9 The ESA-Roscosmos ExoMars Programme

With the encouragement of the Programme Board (PB-HME) and Council, ESA and Roscosmos proceeded to develop further the programme's technical framework. On 14 March 2013 the two agencies signed a cooperation agreement to work in partnership on ExoMars.

The 2016 mission consists of two major elements: 1) The Trace Gas Orbiter (TGO) will search for evidence of methane and other atmospheric gases to acquire information on possible active geological or biological processes; the TGO will also serve as a data relay for surface missions until end 2022; and 2) The Entry, Descent, and Landing Demonstrator Module (EDM) will land on Mars to validate key technologies for the 2018 mission.

[7] The TGO investigators typically held dedicated Orbiter Science Working Team (OSWT) meetings. This is due to the larger participation of US teams, which had an important effect on meeting logistics.

The 2018 mission will deliver the ExoMars rover to the surface of Mars, where it will search for signs of life, past and present. The rover will have the capability to drill to depths of 2 m to collect and analyze samples that have been shielded from the harsh conditions prevailing on the surface, where radiation and oxidants can destroy organic materials. The lander's Surface Platform will be equipped with additional instruments.

ESA and Roscosmos have agreed a well-balanced sharing of responsibilities for the different mission elements. ESA will provide the TGO and EDM in 2016, and the Carrier and Rover in 2018. Roscosmos will be in charge of the 2018 Descent Module and Surface Platform, and will furnish Proton launchers for both missions. NASA will also deliver important contributions to ExoMars, including the Electra Ultra-High Frequency (UHF) radio package for TGO and Mars surface proximity link communications, engineering support to EDM, and a major part of MOMA, the organic molecule characterization instrument on the rover.